

Electron Scattering and Hadron Structure



On behalf of the PionLT and KaonLT Collaborations

Mississippi State University, October 2, 2026



Collaboration Acknowledgement



■ PionLT/KaonLT Spokespersons:

- Dave Gaskell (JLab), Tanja Horn (CUA), GMH (Regina), Pete Markowitz (FIU)

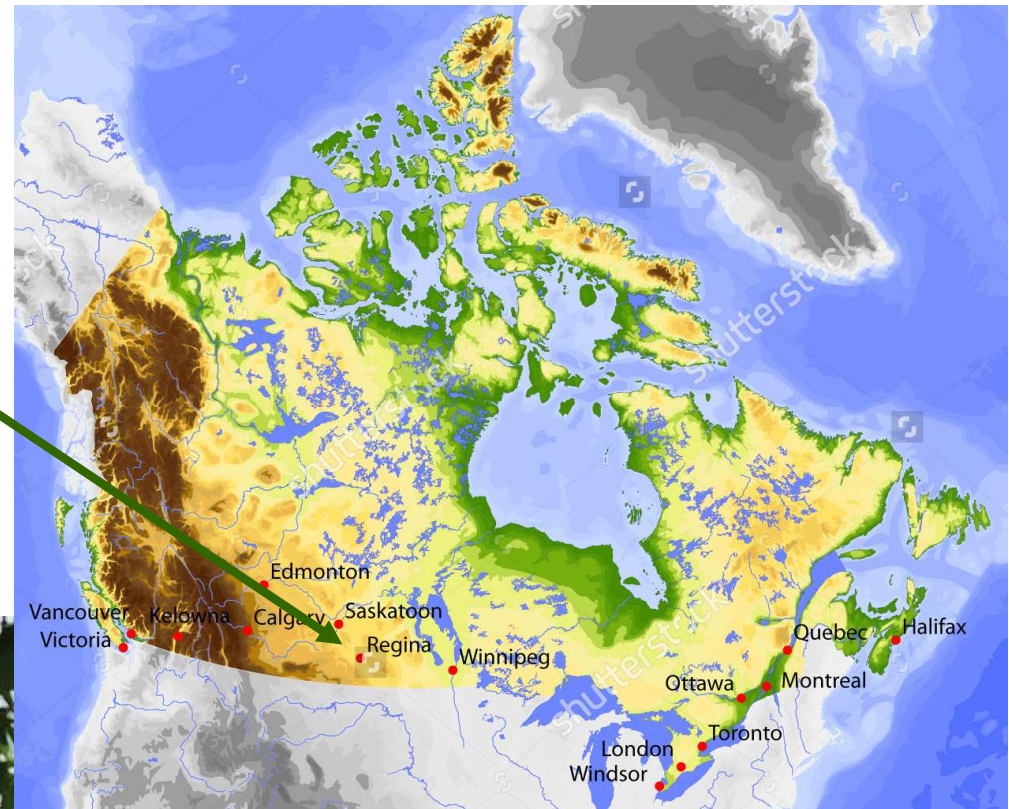
■ PionLT/KaonLT Graduate Students:

- Fernando Chandra (Regina), Nathan Heinrich (Regina), Sameer Jain (CUA), Muhammad Junaid (Regina), Vijay Kumar* (Regina), Alicia Postuma (Regina), Kathleen Ramage (Glasgow), Nermin Sadoun (Regina), Richard Trotta* (CUA), Ali Usman* (Regina) * PhD awarded

■ PionLT/KaonLT Analysis Group:

- Abdennacer Hamdi (Regina), Stephen Kay (Regina/York), Rachel Montgomery (Glasgow), Gabriel Niculescu (JMU), Ioana Niculescu (JMU), Julie Roche (Ohio), Chi Kin Tam (CUA)

Regina, Saskatchewan CANADA



Regina is named after
Queen Victoria, and is
capital of the province of
Saskatchewan
Population: 300,000



University
of Regina

- Founded 1974
- 16,650 students, incl. 2,240 Grad Students (Oct 2025)
- Physics Dept. offers B.Sc., M.Sc. and Ph.D. degrees

Quantum Electrodynamics

Quantum Chromodynamics

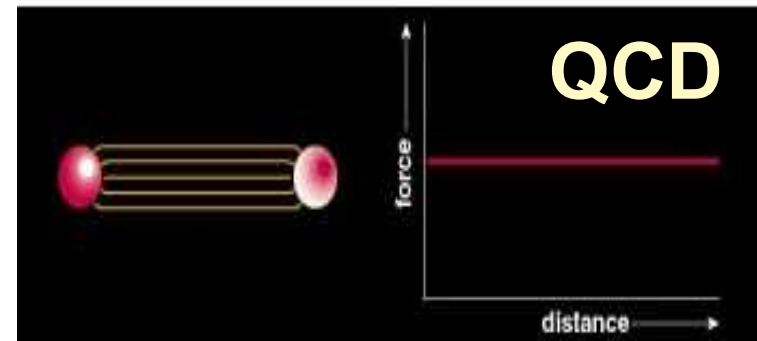
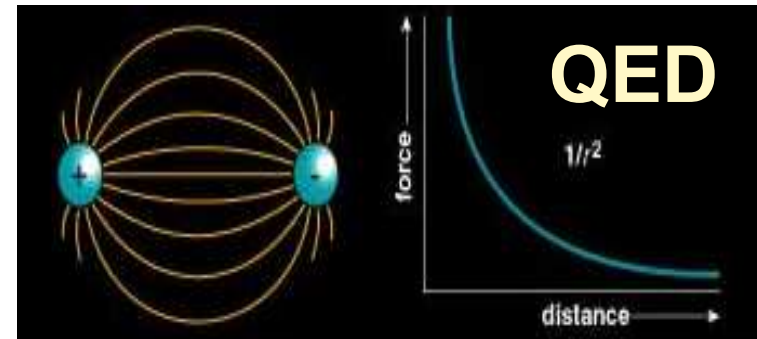
three generations of matter (fermions)			interactions / forces (bosons)	
	I	II	III	
mass	$\approx 2.16 \text{ MeV}$	$\approx 1.27 \text{ GeV}$	$\approx 173 \text{ GeV}$	$\approx 125 \text{ GeV}$
charge	$+2/3$	$+2/3$	$+2/3$	0
spin	$1/2$	$1/2$	$1/2$	0
	u up	c charm	t top	g gluon
	d down	s strange	b bottom	γ photon
	e electron	μ muon	τ tau	W W boson
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z Z boson
				H Higgs

QUARKS

LEPTONS

GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS



- Quarks are fractionally charged and interact via the electromagnetic (QED) and strong (QCD) interactions.
- Unlike the photons of QED, the gluons of QCD carry color charge and interact strongly, leading to the confinement of quarks inside hadrons.

Hadrons

Quarks (and their color charge) are confined inside strongly-interacting particles called hadrons

Two families of hadrons:

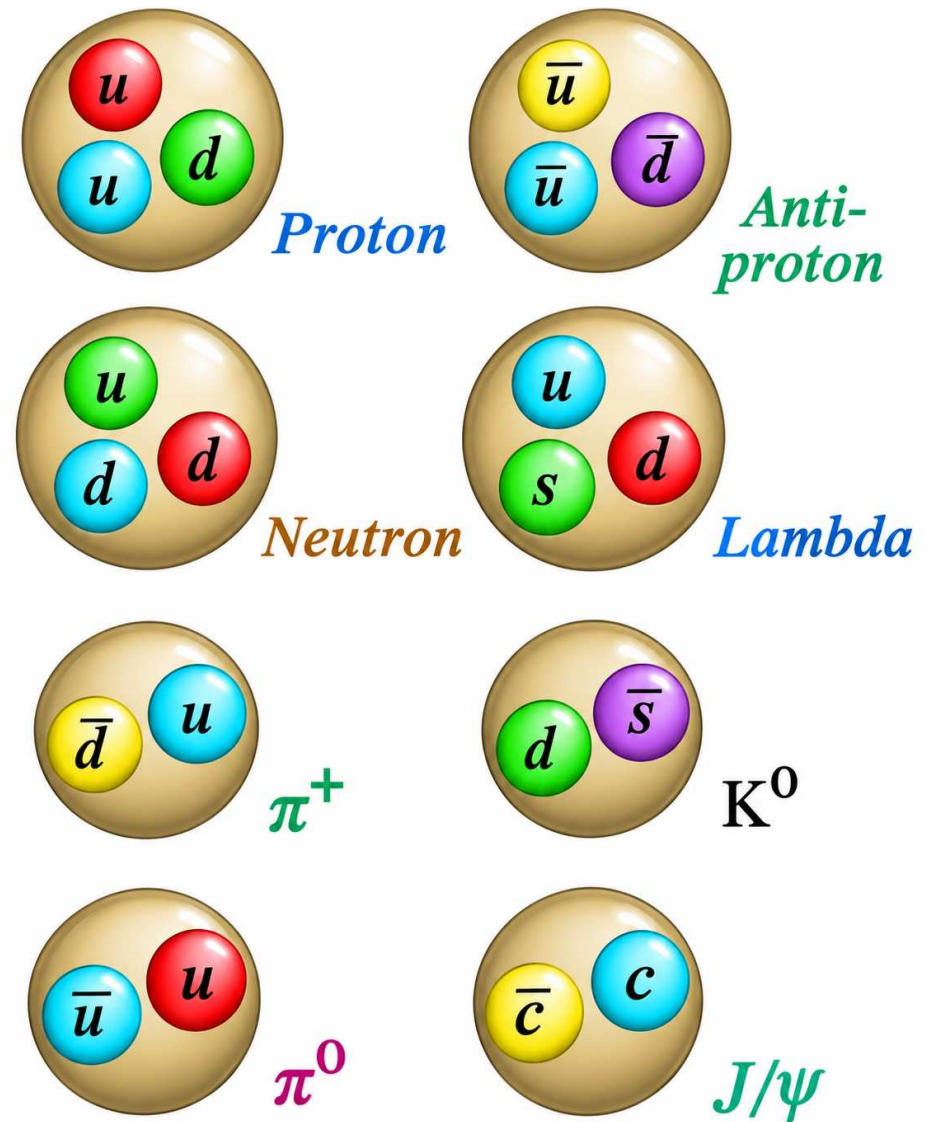
Baryons:

- Bosons (integer spin)
- Valence qqq structure

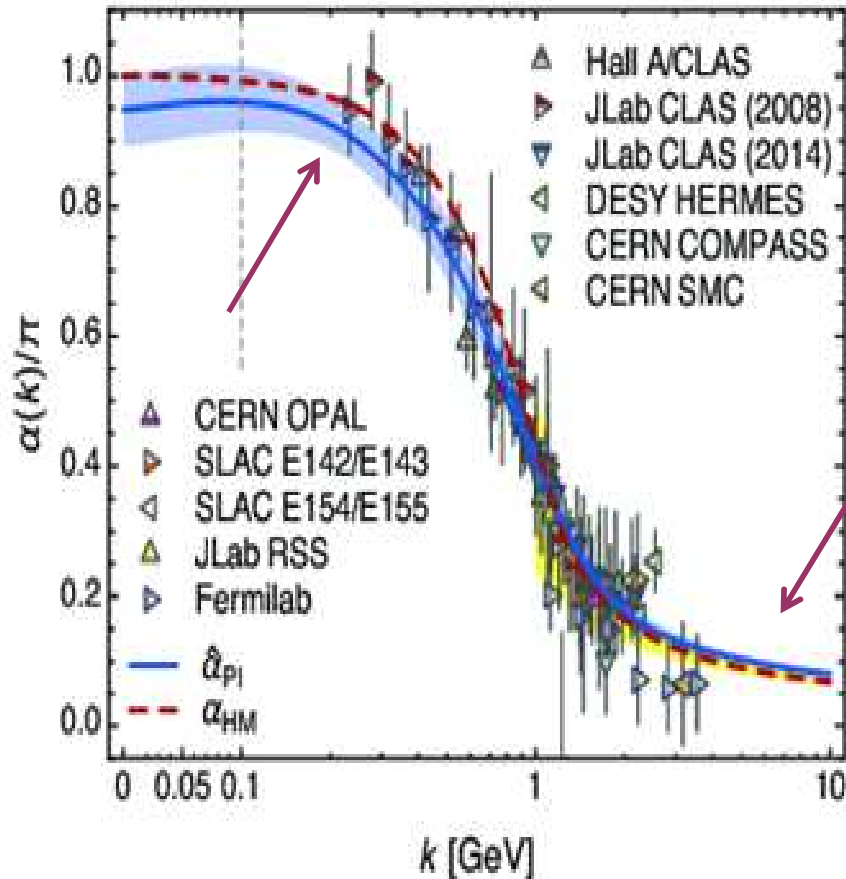
Mesons:

- Fermions (half-integer spin)
- Valence $q\bar{q}$ structure

Gluons and virtual quarks also contribute to hadron structure



QCD's Dual Nature



Binosi, Mezrag, Papavassiliou,
Roberts, Rodriguez-Quintero,
PRD 96 (2017) 054026

Short Distance Interaction:

- Short distance quark-quark interaction is feeble.
 - Quarks inside protons behave as if they are nearly unbound, pQCD.
 - Asymptotic Freedom.
 - Nobel prize: Friedman, Kendall and Taylor, 1990.

Long Distance Interaction:

- Quarks strongly bound within hadrons.
 - Color confinement (strong QCD).
 - Quantitative QCD description of nucleon's properties (i.e. understanding of the confinement regime) remains a puzzle!

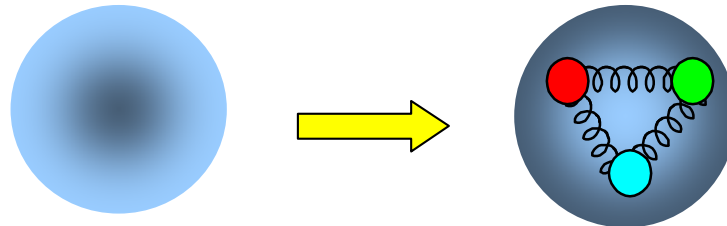
Quantum Chromodynamics (QCD) in the confinement regime: How does it work?

What do we know?

QCD works in the perturbative (weak) regime

Many experimental tests led to this conclusion, example:

- Proton is not point-like; Elastic electron scattering (Nobel Prize: Hofstadter, 1961).
- Quarks and gluons/Partons are the constituents; Deep Inelastic electron Scattering (Nobel prize: Friedman, Kendall and Taylor, 1990).



Theory achievements celebrated

Asymptotic freedom (Nobel prize: Gross, Politzer and Wilczek, 2004),

but

Quantitative QCD description of the nucleon's properties
(i.e. understanding of the color confinement regime) remains a
puzzle!

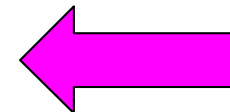
Physics Problems for the Next Millennium

Selected by:

Michael Duff, David Gross, Edward Witten

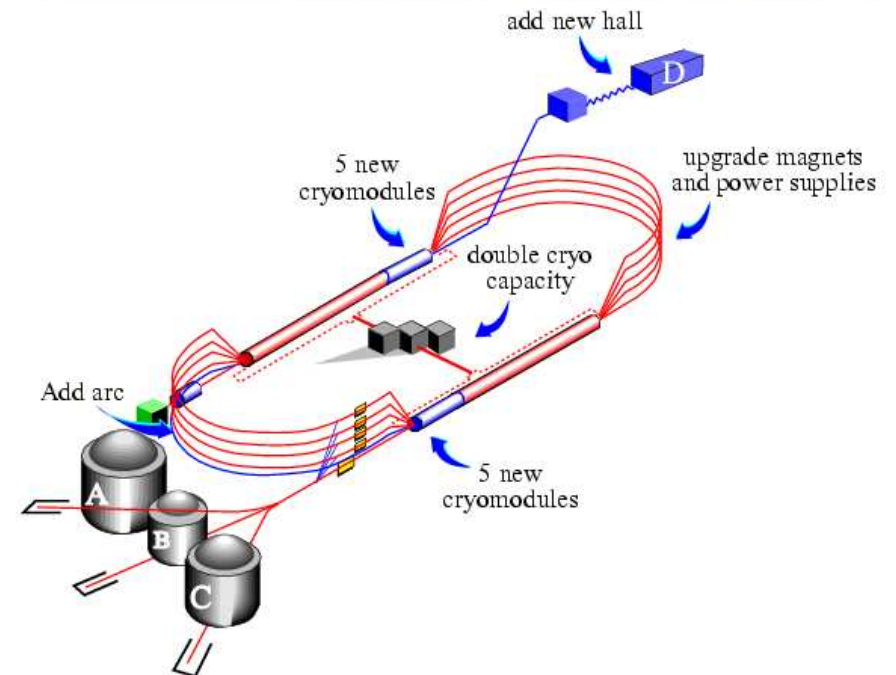
Strings 2000

1. Size of dimensionless parameters.
2. Origin of the Universe.
3. Lifetime of the Proton.
4. Is Nature Supersymmetric?
5. Why is there 3+1 Space-time dimensions?
6. Cosmological Constant problem.
7. Is M-theory fundamental?
8. Black Hole Information Paradox.
9. The weakness of gravity.
10. Quark confinement and the strong force.



Jefferson Lab

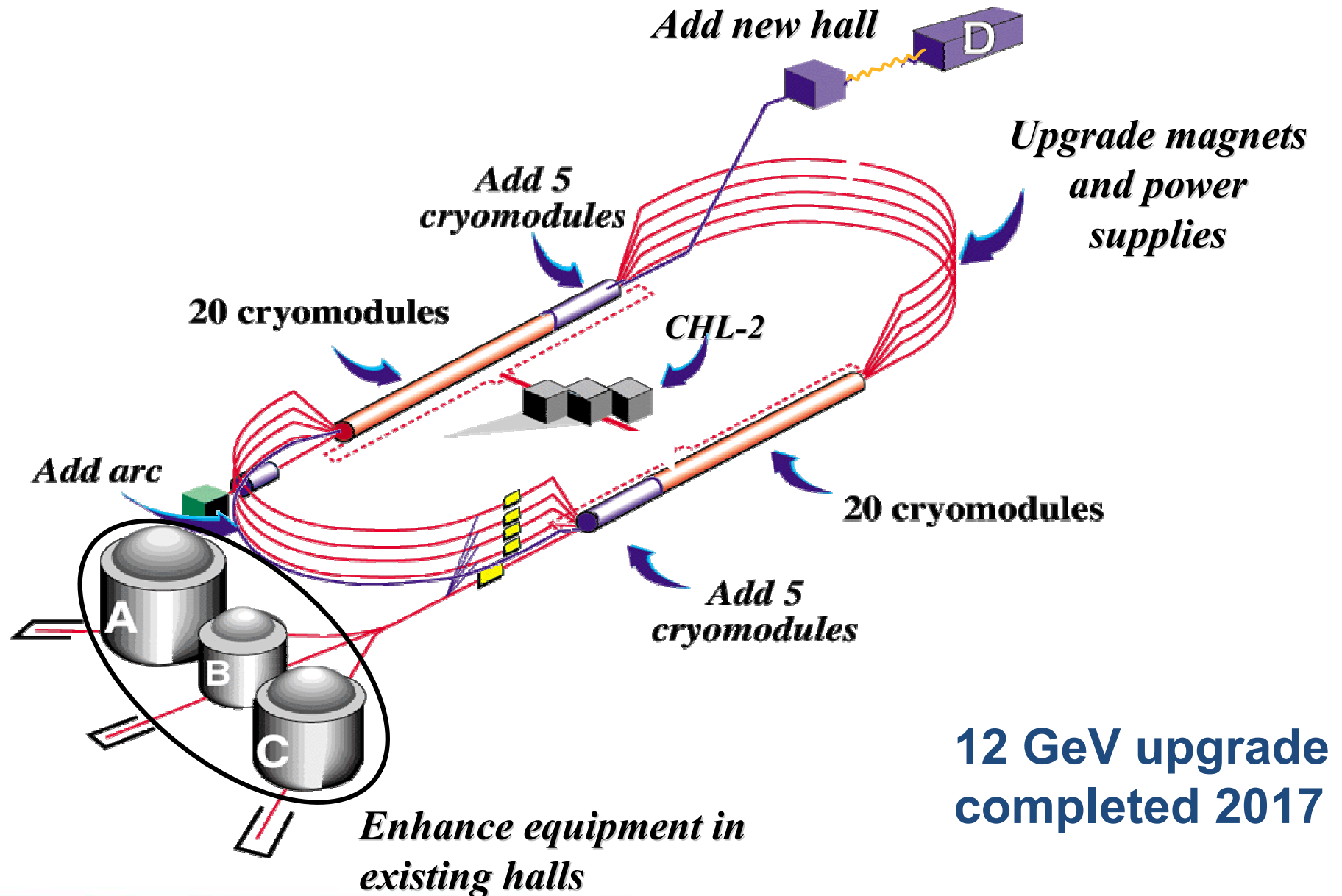
Thomas Jefferson National Accelerator Facility



Two 1.5 GHz Superconducting Linear Accelerators provide electron beam for Nucleon & Nuclear structure studies.

- **Beam energy $E \rightarrow 12$ GeV.**
- **Beam current $>100 \mu\text{A}$.**
- **Duty factor 100%, 85% polarization.**
- **Experiments in all 4 Halls can receive beam simultaneously.**

Jefferson Lab – 12 GeV Upgrade



Why electron scattering experiments?

Transition from pQCD to Strong QCD needs data with high precision for a quantitative understanding of color confinement.

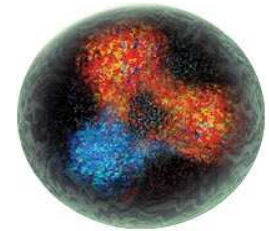
1990's advancements:

Intense CW electron beams.
Polarized targets/polarimetry.
Improvement in polarized e sources.

Luminosity:

(SLAC, 1978) $\sim 8 \times 10^{31} \text{ cm}^{-2}\text{-s}^{-1}$
(JLab, 2000) $\sim 4 \times 10^{38} \text{ cm}^{-2}\text{-s}^{-1}$

$$d = 1 \rightarrow 0.1 \text{ fm} \quad \Leftrightarrow \quad Q^2 = 0.1 - 10 (\text{GeV}/c)^2$$



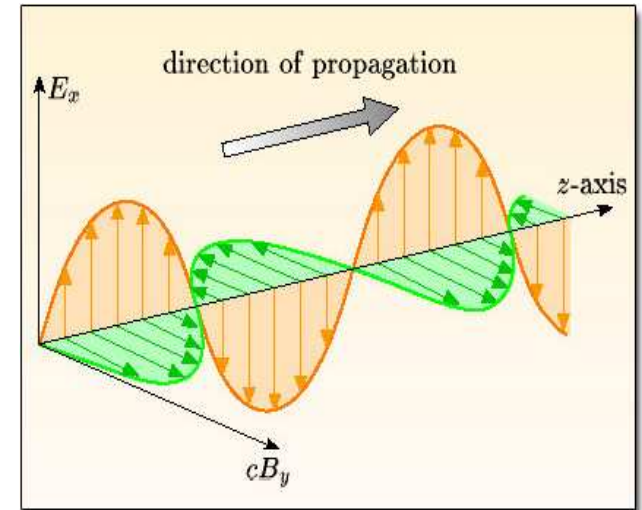
What quantities do we measure?

- Hadron form factors: pion, nucleon. [System responds coherently]
- Nucleon structure functions: [System responds incoherently]

Probing Hadrons via well-known Electromagnetic Interaction

Real Photons (γ):

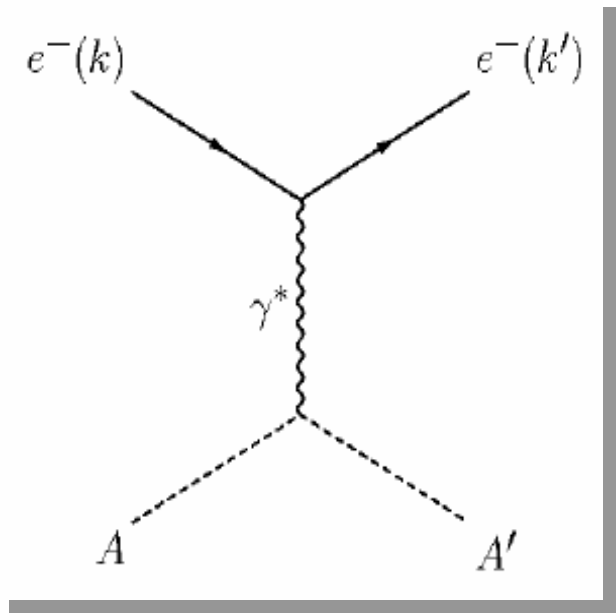
- *Created in hard electron deceleration (Bremsstrahlung).*
- *Zero Rest Mass: $E=pc$*
- *Equivalently: $Q^2=p^2c^2-E^2=0$*
- *Observation Scale: $R \approx h/p$*
- *Electric Polarization Transverse to Propagation*



Virtual (Spacelike) Photons (γ^*):

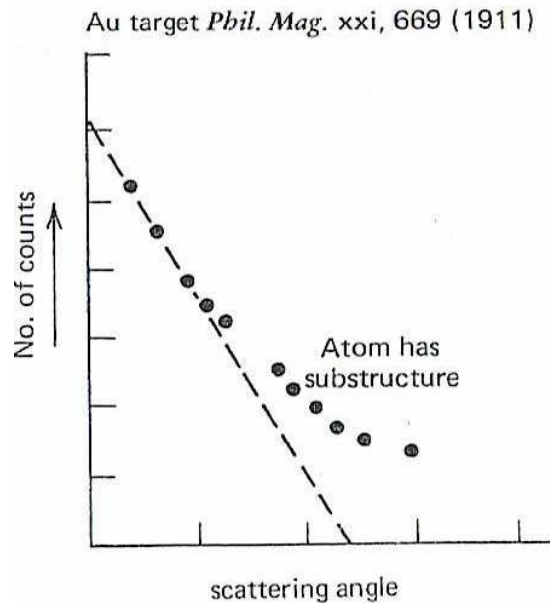
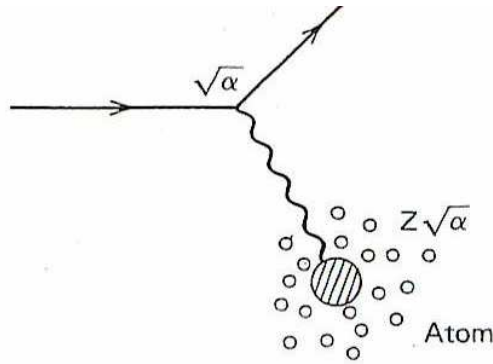
- *Created in larger θ electron scattering.*
- *$E \neq pc$: Heisenberg Principle: $\Delta E \Delta t \geq \hbar/2$*
- *$Q^2 = p^2c^2 - E^2 > 0$*
If we define $m^2c^4 = E^2 - p^2c^2$, then $Q^2 > 0$ implies imaginary virtual photon mass
- *Observation Scale: $R \approx (\hbar c)/Q$*
- *Transverse and Longitudinal Electric Polarizations permitted*

$$\begin{aligned}\text{Virtual Photon Energy} &= E - E' \\ \text{Virtual Photon Momentum} &= \vec{k} - \vec{k}'\end{aligned}$$



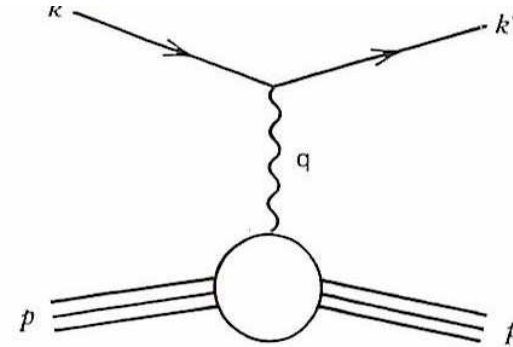
Rutherford Scattering

Scattering
of α particle
by atom

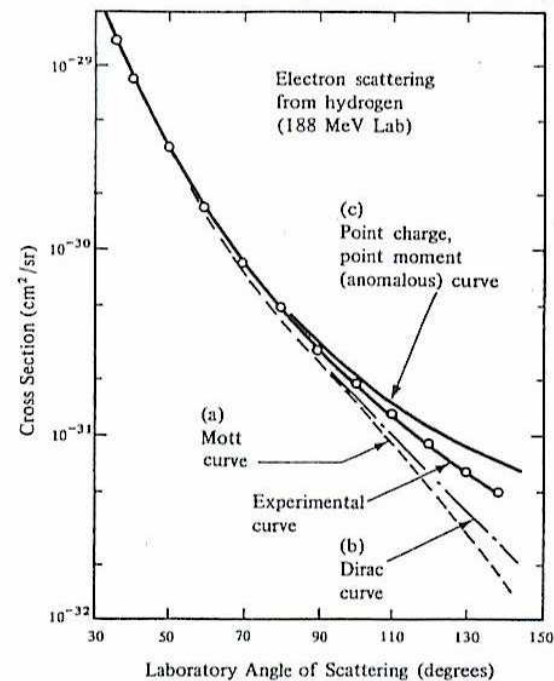


Proton Form Factor

Scattering
of electron
by proton



Electron-proton scattering with 188 MeV electrons. [R. W. McAllister and R. Hofstadter, *Phys. Rev.* **102**, 851 (1956).]



Elastic Form Factors

In general, the elastic scattering cross section from an extended target is

$$\left(\frac{d\sigma}{d\Omega} \right) = \left(\frac{d\sigma}{d\Omega} \right)_{\text{point object}} \left| F(Q^2) \right|^2$$

In the case of an infinitely massive target, the form factor is simply the Fourier transform of the charge distribution.

$$F(Q^2) = \int \rho(\vec{x}) e^{i\vec{q} \cdot \vec{x} / \hbar} d^3x$$

Spin 0 mesons (π^+, K^+): electric charge form factor (F) only.

Spin $\frac{1}{2}$ Nucleon: electric (G_E) and magnetic (G_M) form factors.

→ alternate representation in terms of spin non-flip (F_1) and spin flip (F_2) form factors.

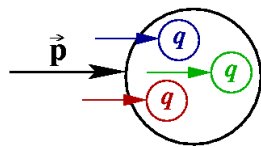
The measurements allow us to test our understanding of hadronic structure by comparison to QCD-based predictions.

An early pQCD Prediction:

- Dimensional Scaling at Large Momentum

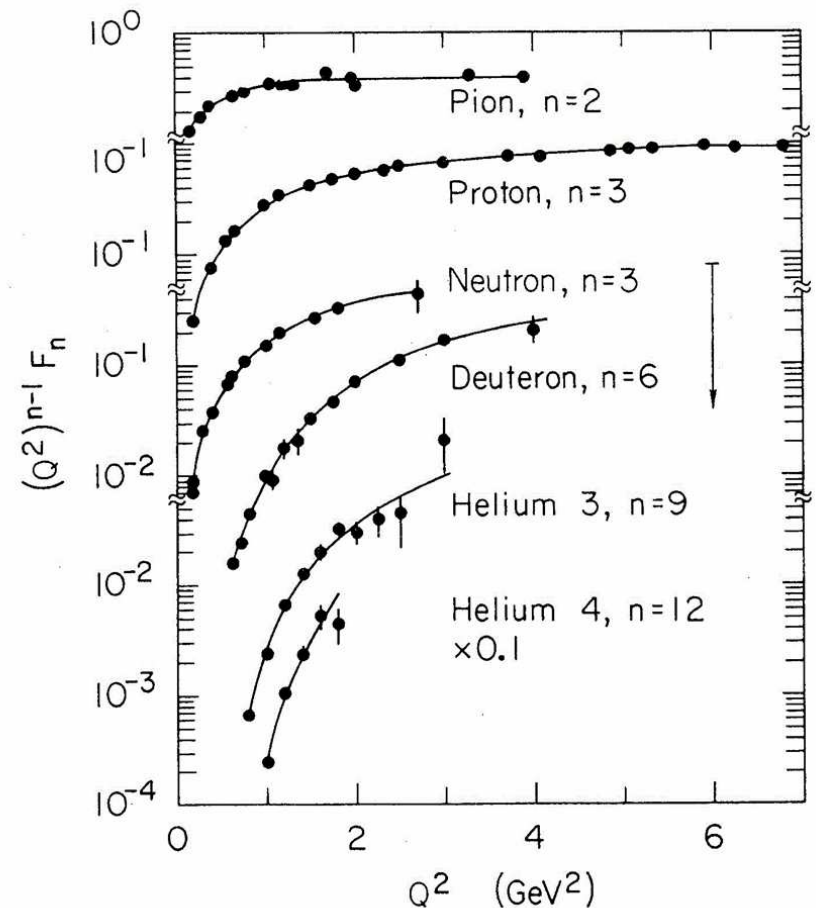
At infinite momentum, quarks are asymptotically free.

- Equivalent to turning off the strong interaction.
- The hadron becomes a collection of free quarks with equal longitudinal momenta.



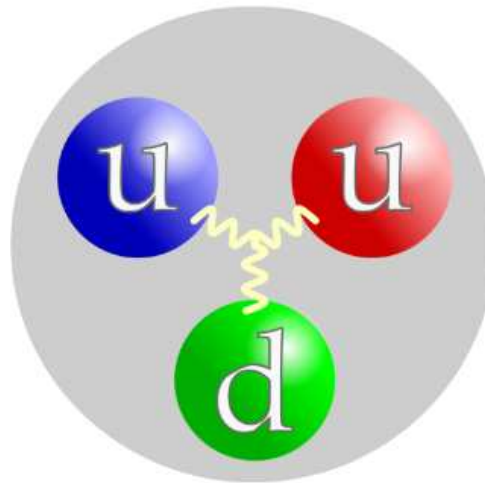
Dimensional analysis of the hadron scattering amplitude in terms of the participating fields yields

$$F(Q^2) \propto \frac{1}{(Q^2)^{n-1}}$$



S.J. Brodsky, G.P. Lepage "Perturbative QCD",
A.H. Mueller, ed., 1989.

Nucleon (proton, neutron) Form Factors



Spin 1/2: Elastic electron scattering from nucleons

pQCD Dimensional Scaling Rule:

- $F_1(Q^2) \sim 1/Q^4$ ($n=3$).
- $F_2(Q^2) \sim 1/Q^6$ ($n=3$ with spin flip).
 - $Q^2 F_2/F_1 \sim \text{constant}$.
- Data indicate onset of pQCD scaling at only $Q^2 \approx 2 \text{ GeV}^2$!

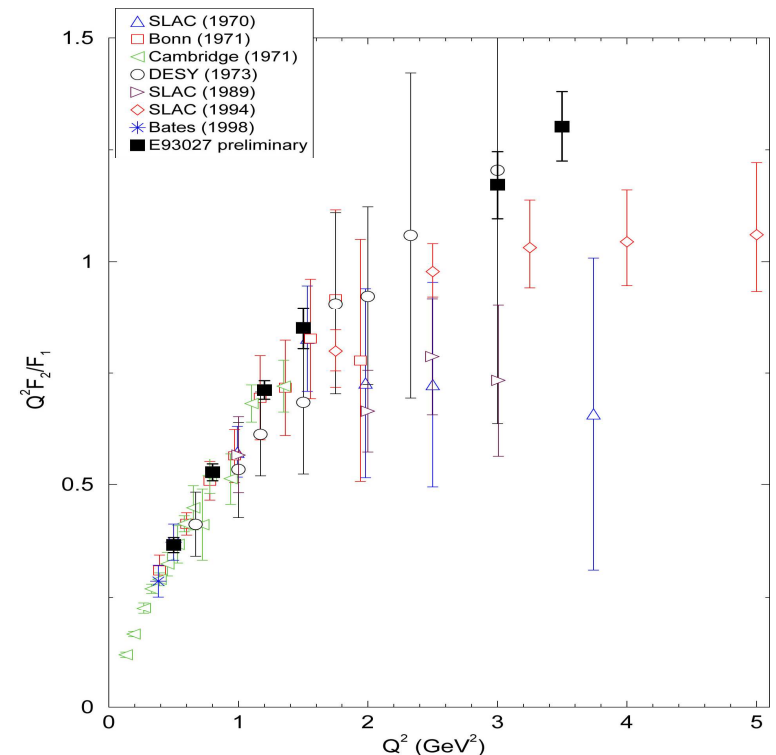
Magnetic contribution dominates proton cross section at high Q^2 :

- F_1 data of fairly good quality.

Electric contribution at few % level:

- F_2 difficult to measure.
- Systematic error issues.

World proton data set, 1997



F_1 (Dirac FF) = helicity-conserving

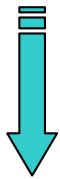
F_2 (Pauli FF) = helicity-flip contribution

“Rosenbluth” L/T Separation Technique

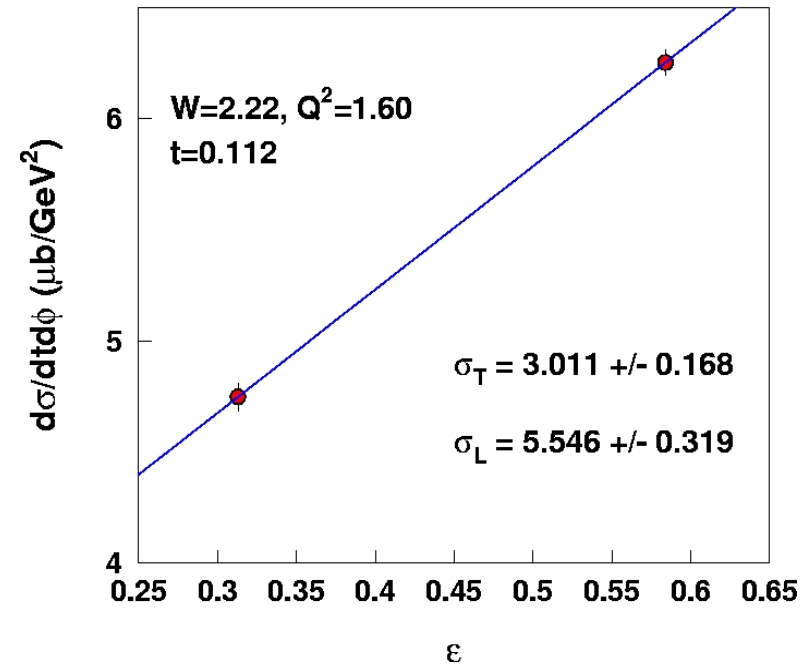
A challenging technique that requires the delicate comparison of data at two different electron beam energies.

Virtual-photon polarization:

$$\varepsilon = \left(1 + 2 \frac{(E_e - E_{e'})^2 + Q^2}{Q^2} \tan^2 \frac{\theta_{e'}}{2} \right)^{-1}$$



$$\frac{d\sigma^{el}}{dQ^2} \rightarrow \varepsilon G_E(Q^2) + \tau G_M(Q^2)$$



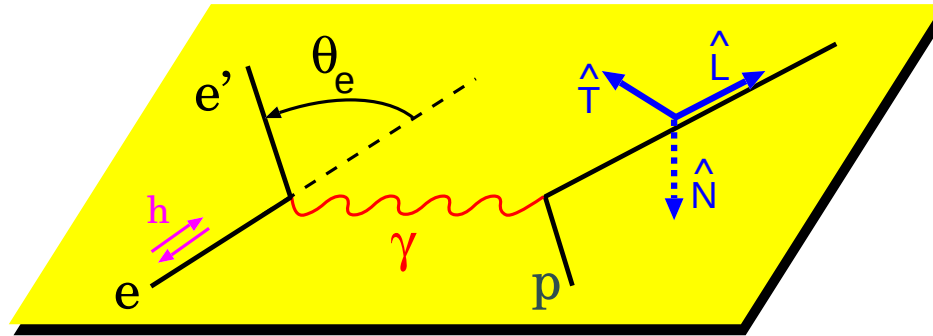
Magnetic contribution dominates proton cross section at high Q^2 :

- G_M data of fairly good quality ($G_M = F_1 + F_2$)

Electric contribution at few % level:

- G_E difficult to measure ($G_E = F_1 - \tau F_2$)
- Systematic error issues.

Polarization transfer technique



- Technique developed at Novosibirsk, Russia
- Requires an intense polarized electron beam and Focal Plane Polarimeter to measure the polarization of the recoil nucleon.

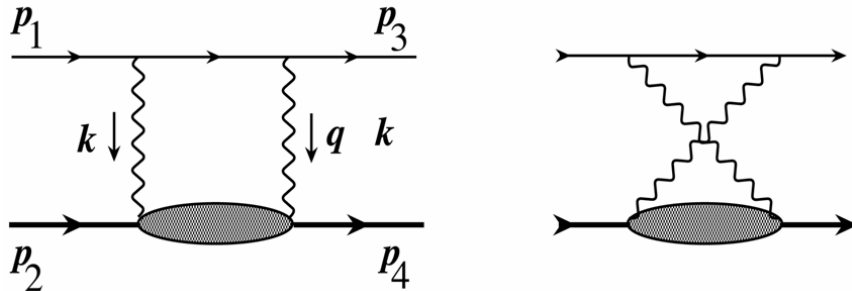
$$\frac{G_E}{G_M} = -\frac{p_t}{p_l} \frac{E + E'}{2m} \tan\left(\frac{\theta_e}{2}\right)$$

- Simultaneous measurement of transverse and longitudinal polarization components provides an accurate measurement of the form factor ratio.

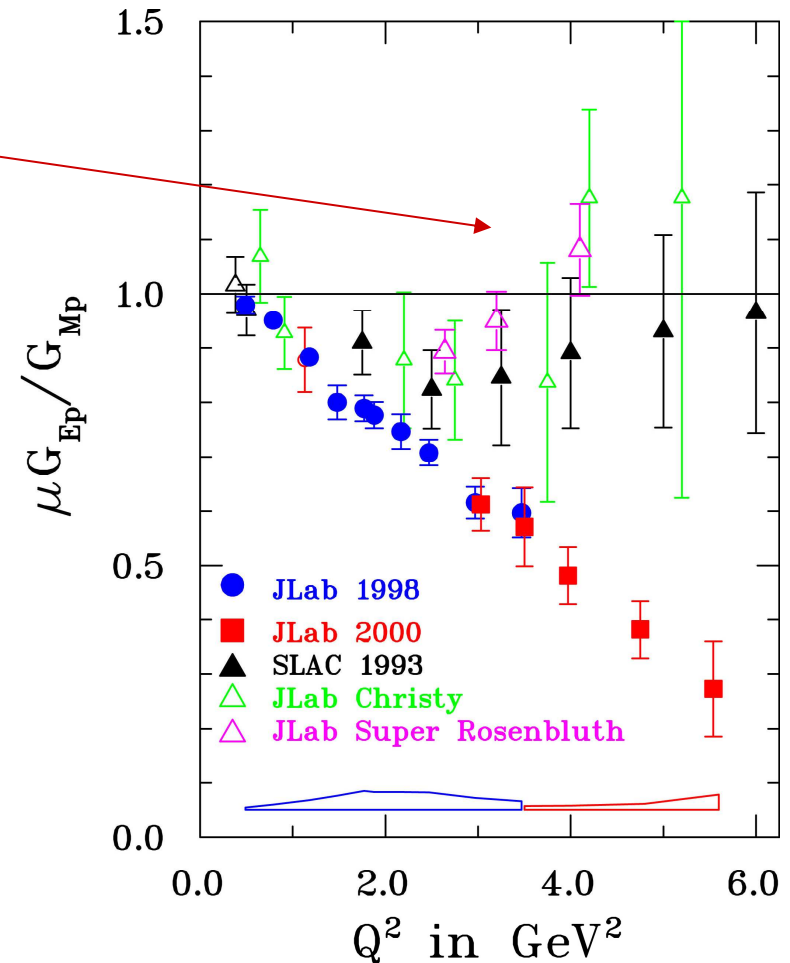
Comparison of Polarization and Rosenbluth techniques

2004 JLab “SuperRosenbluth”
(e,p) cross sections data agree
well with global cross section fit.
[I.A. Qattan et al, PRL **94** (2005) 142301]

Likely culprit: 2- γ exchange
impacts cross section data.
[P. Blunden et al, PRL **91** (2003) 142304]



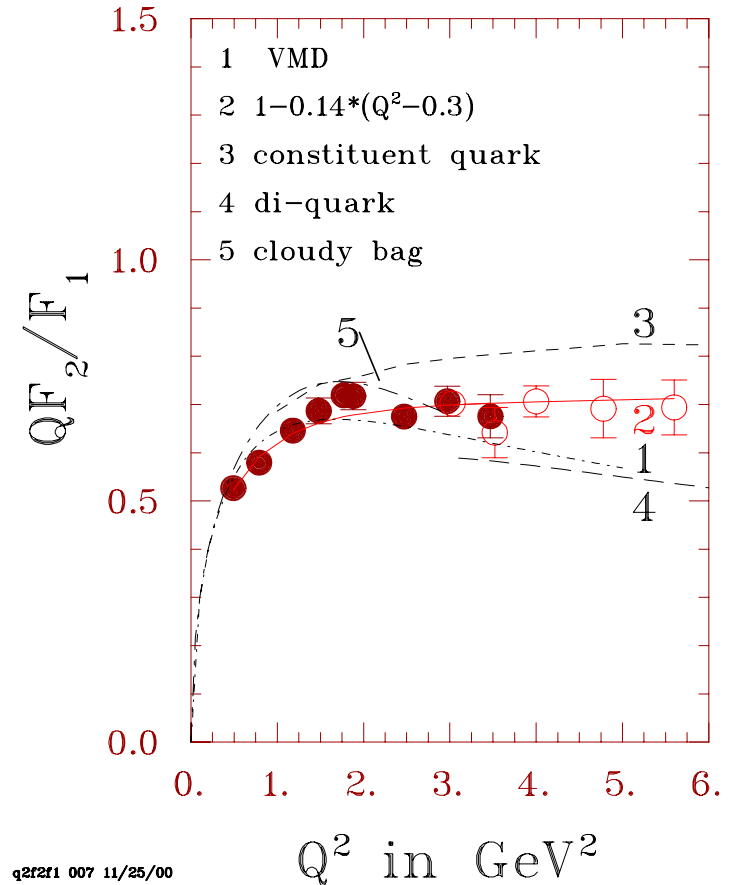
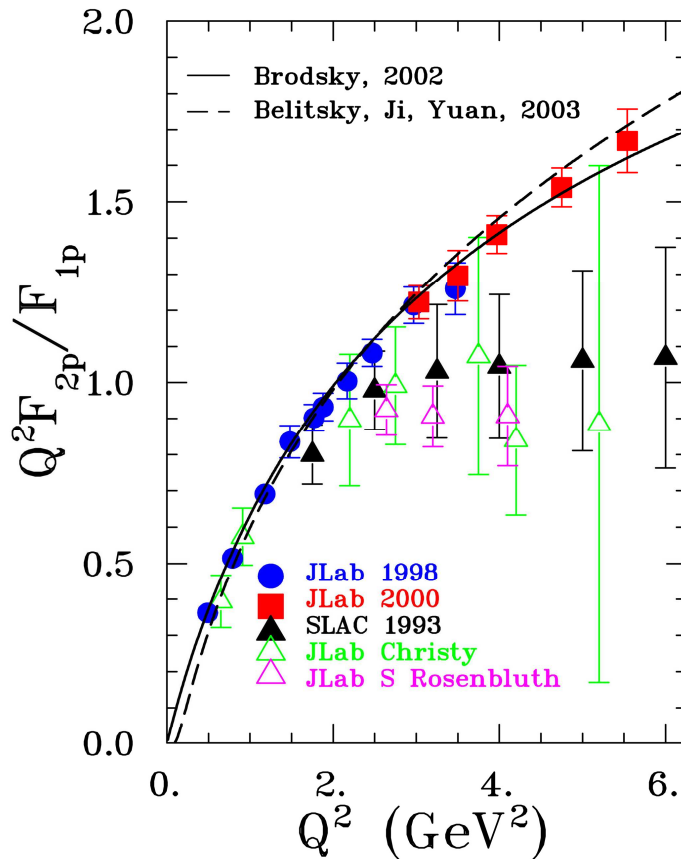
Can be directly tested with
 $\sigma(e^+)/\sigma(e^-)$ (Novosibirsk, JLab).



O. Gayou et al, PRL **88** (2002) 092301

WHAT THIS MEANS: Elastic
cross sections are accurate, but the
polarization transfer measurements
better represent G_E^p .

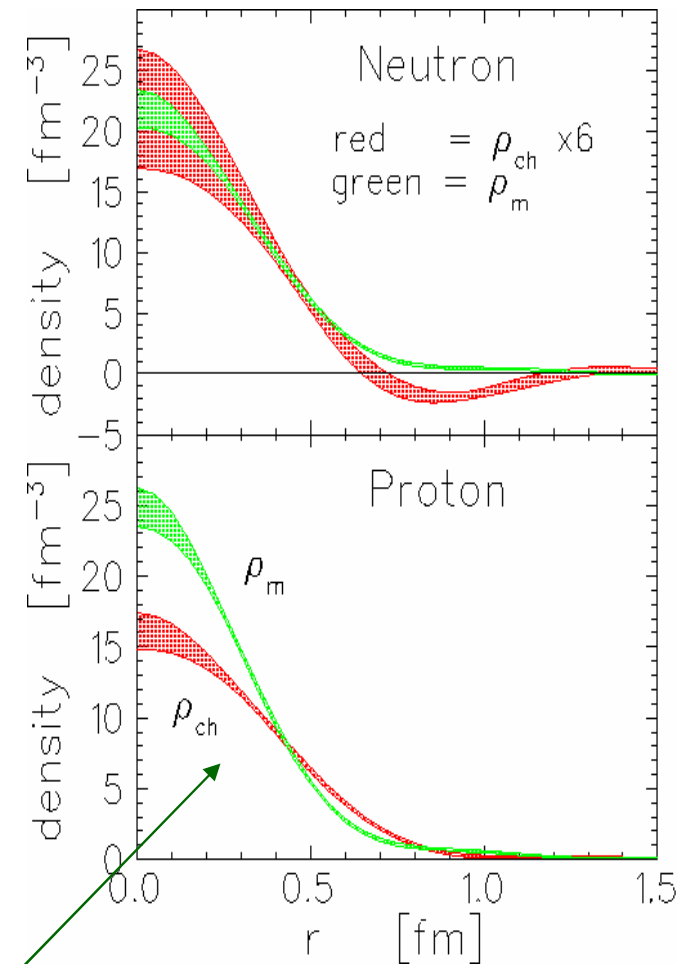
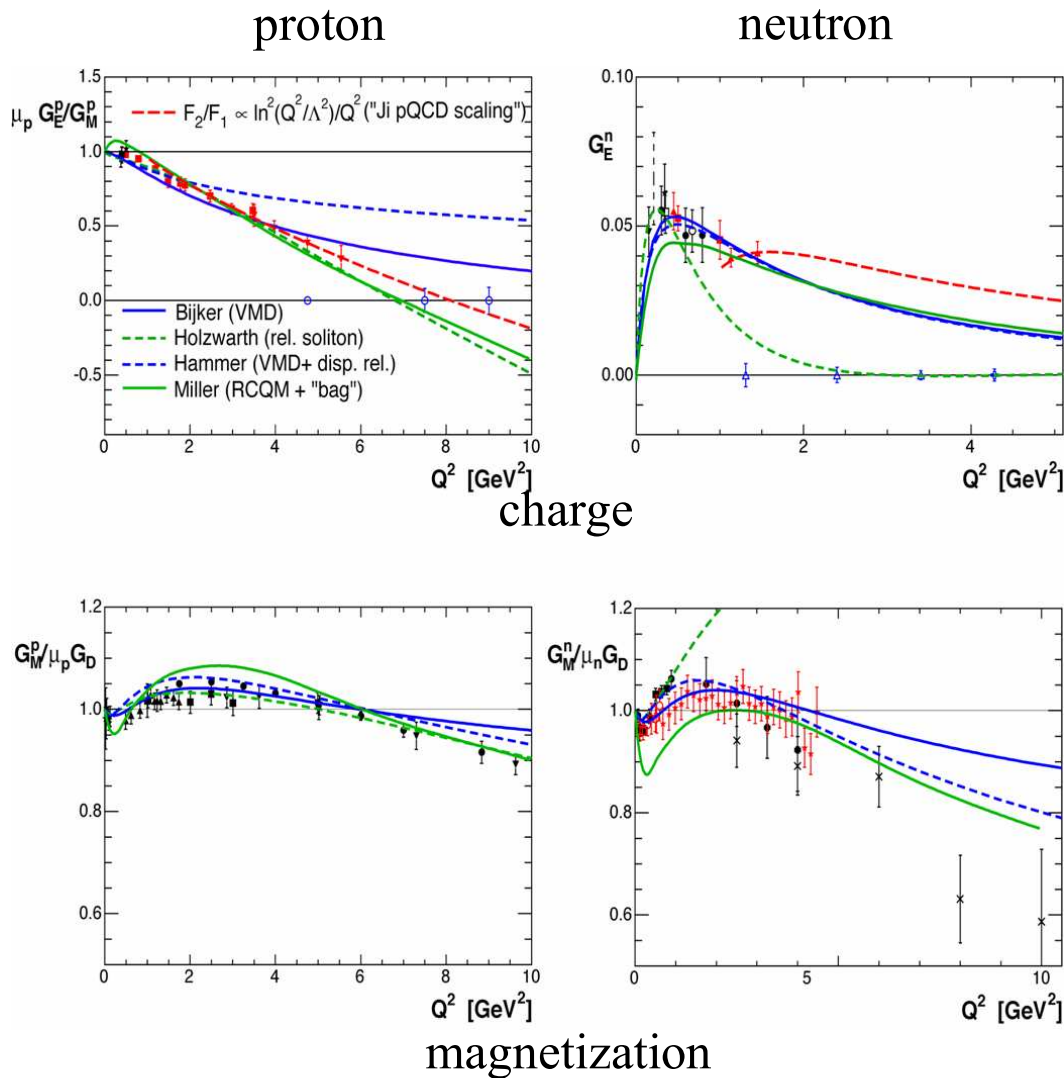
Jefferson Lab Proton F_2/F_1 Data



- JLab data show that Q^2 scaling was “premature”
- The data instead show a remarkable scaling with Q , which was not anticipated by theory.
- Higher twist and other soft contributions produce $\ln(Q^2)$ corrections which give rise to Q -like scaling [Belitsky, Ji, Yuan, PRL **91** (2003) 092003]

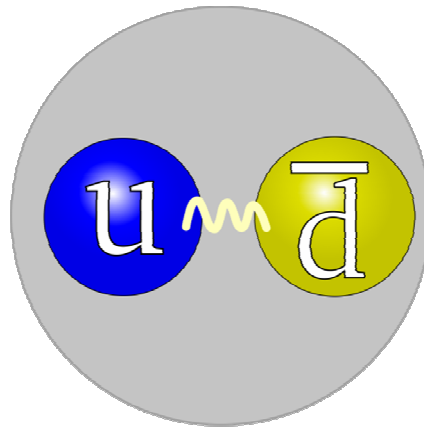
Global analysis of p and n Form Factors

J.J. Kelly, PRC **66** (2002) 065203



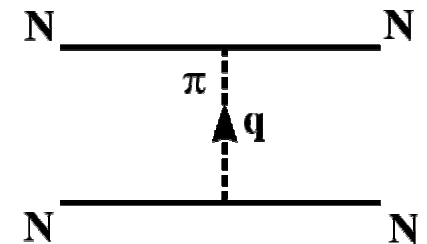
JLab polarization data
show depletion of
charge in proton interior.

Charged Meson Form Factors



The Pion has Particular Importance

- The pion is responsible for the long-range part of the nuclear force, acting as the basis for meson exchange forces, and playing a critical role as an elementary field in nuclear structure Hamiltonians.



- As the lightest meson, it must be a valence $q\bar{q}$ bound state, but understanding its structure through QCD has been exceptionally challenging.
 - e.g. Constituent Quark Models that describe a nucleon with $m_N=940$ MeV as a qqq bound state, are able to describe the ρ -meson under similar assumptions, yielding a constituent quark mass of about

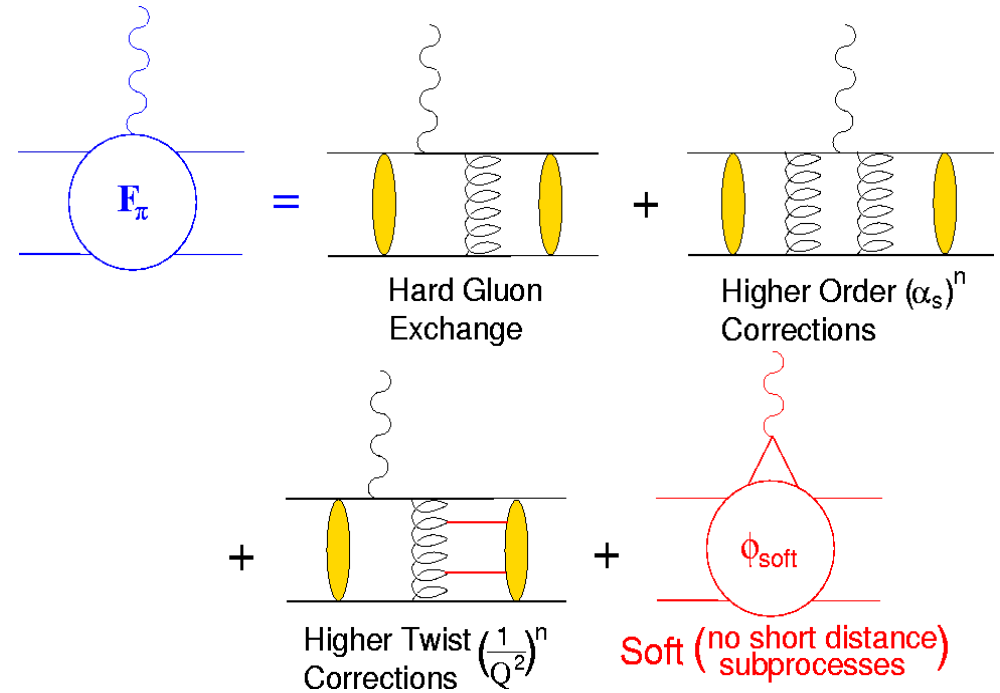
$$m_Q \approx \frac{m_N}{3} \approx \frac{m_\rho}{2} \approx 350 \text{ MeV}$$

- The pion mass $m_\pi \approx 140$ MeV seems “too light”.
- **We exist because nature has supplied two light quarks and these quarks combine to form the pion, which is unnaturally light and hence very easily produced.**

Meson Form Factors and QCD

- The simple $q\bar{q}$ valence quark structure of mesons presents the ideal laboratory for testing our understanding of bound quark systems

→ all hadronic structure models use the π^+ as a test case.
“The positronium atom of QCD”

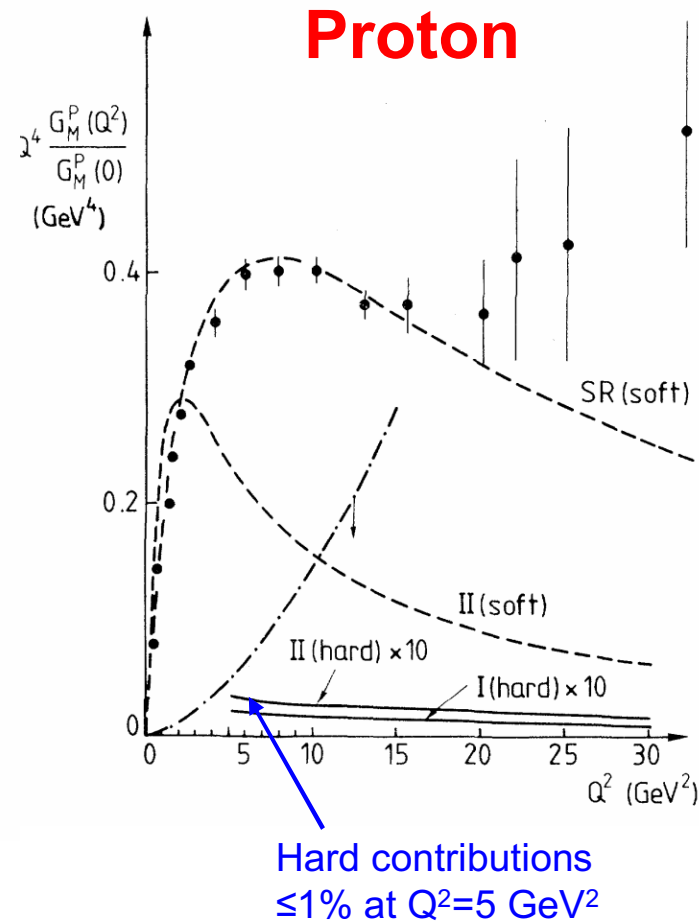
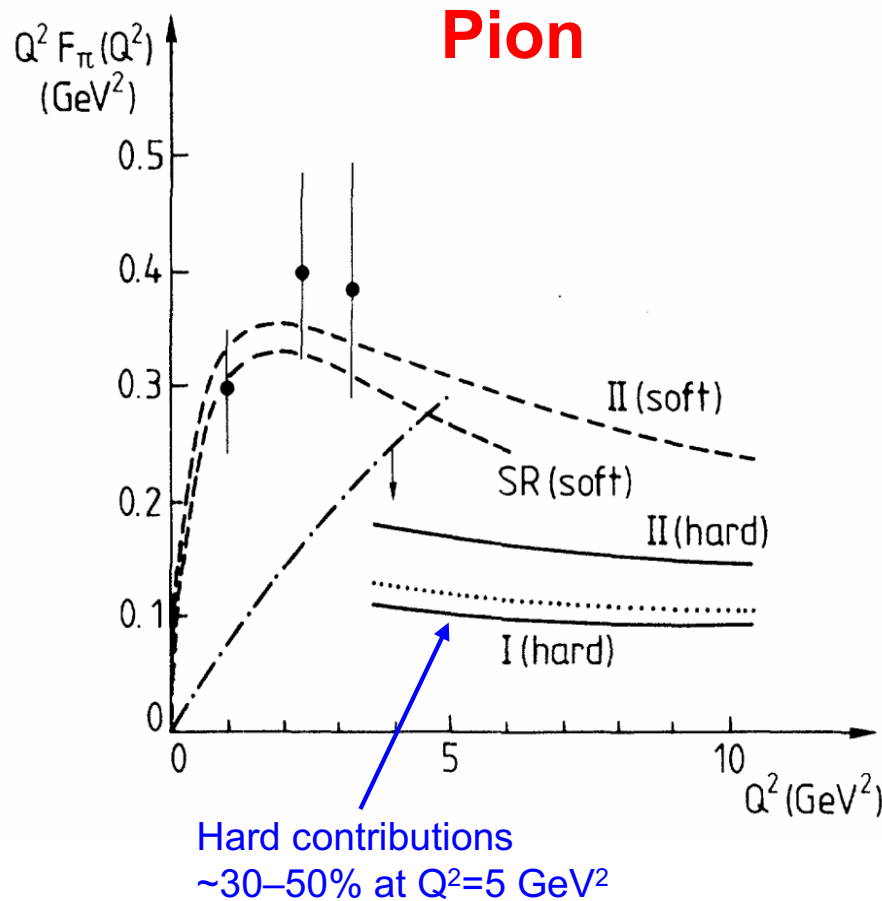


Excellent opportunity for studying the **QCD transition** from effective degrees of freedom to quarks and gluons.

i.e. from the **strong QCD** regime to the **hard QCD** regime.

Jefferson Lab is the only experimental facility capable of the necessary measurements.

The Pion as a QCD Laboratory



Isgur & Llewellyn-Smith, PRL **52**(1984)1080

The transition from the Soft to Hard QCD regime is best observed experimentally with simple systems such as the π^+ form factor

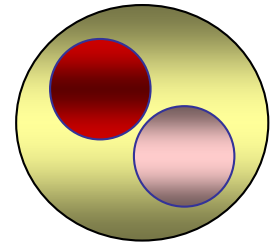
Spin 0: π and K Electromagnetic Form Factors

At low $Q^2 < 0.3 \text{ GeV}^2$ the $\pi^+(K^+)$ form factor can be measured exactly using high energy $\pi^+(K^+)$ scattering from atomic electrons

300 GeV experiment at
CERN SPS measures
 $\pi^+(K^+)$ charge radii:

$$r_\pi = 0.672 \pm 0.008 \text{ fm}$$

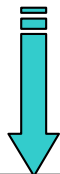
$$r_K = 0.560 \pm 0.031 \text{ fm}$$



To access higher Q^2 one must use an experimentally “unclean”: moving virtual target...

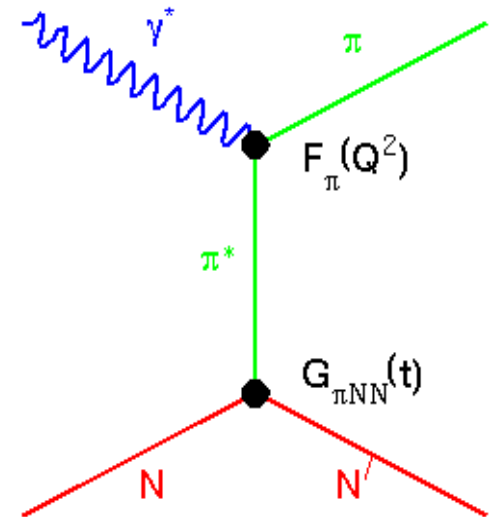
$$|p\rangle = |p\rangle_0 + |n\pi^+\rangle + \dots$$

$$2\pi \frac{d\sigma}{dtd\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)} \frac{d\sigma_{LT}}{dt} \cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$$



$$\varepsilon = [1 + 2(1 + \tau) \tan^2(\theta/2)]^{-1}$$

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t - m_\pi^2)^2} g_{\pi NN}^2(t) F_\pi^2(Q^2, t)$$

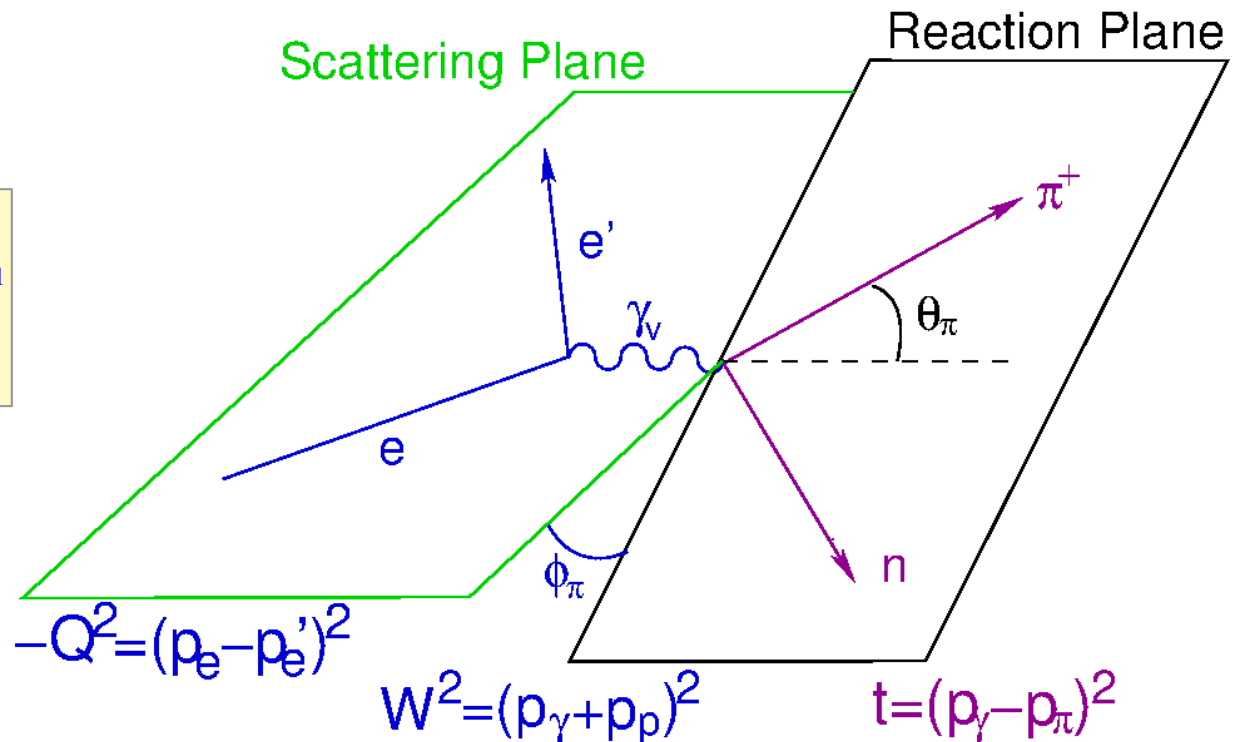


$$2\pi \frac{d^2\sigma}{dt d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)} \frac{d\sigma_{LT}}{dt} \cos \phi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$$



Virtual-photon polarization:

$$\varepsilon = \left(1 + 2 \frac{(E_e - E_{e'})^2 + Q^2}{Q^2} \tan^2 \frac{\theta_{e'}}{2} \right)^{-1}$$



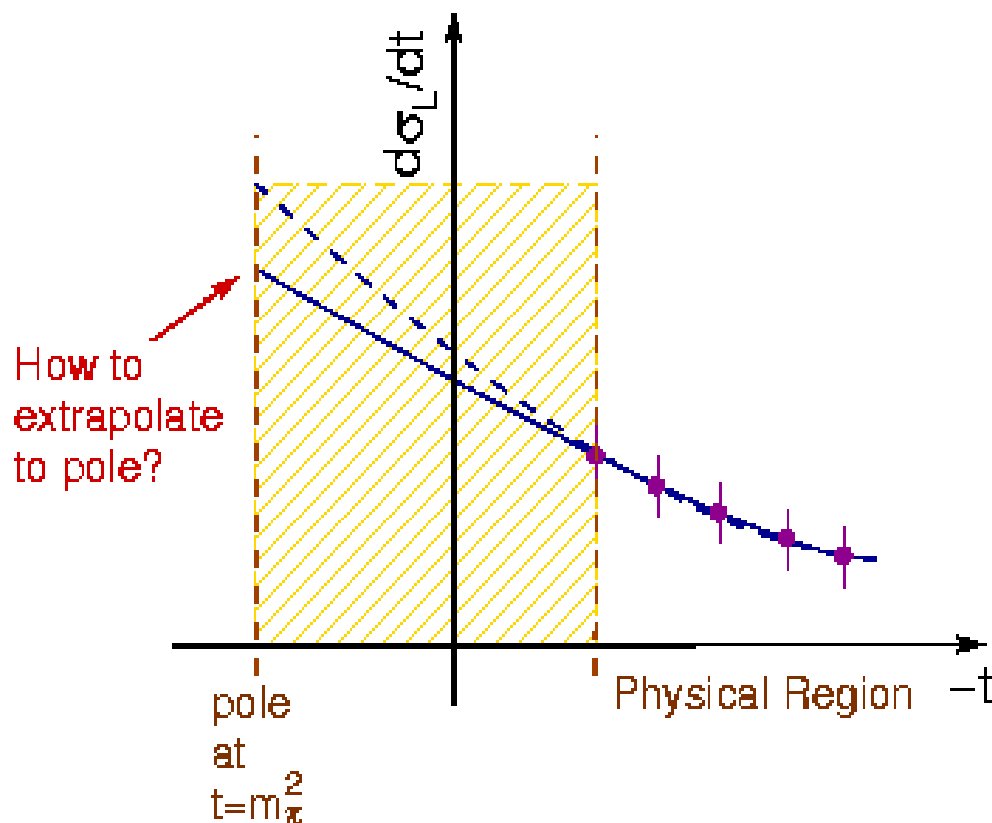
- L-T separation required to separate σ_L from σ_T
- Need to take data at smallest available $-t$, so σ_L has maximum contribution from the π^+ pole
- Need to measure t -dependence of σ_L at fixed Q^2, W

Extraction of form factor from σ_L data

PION Charge Form Factor:

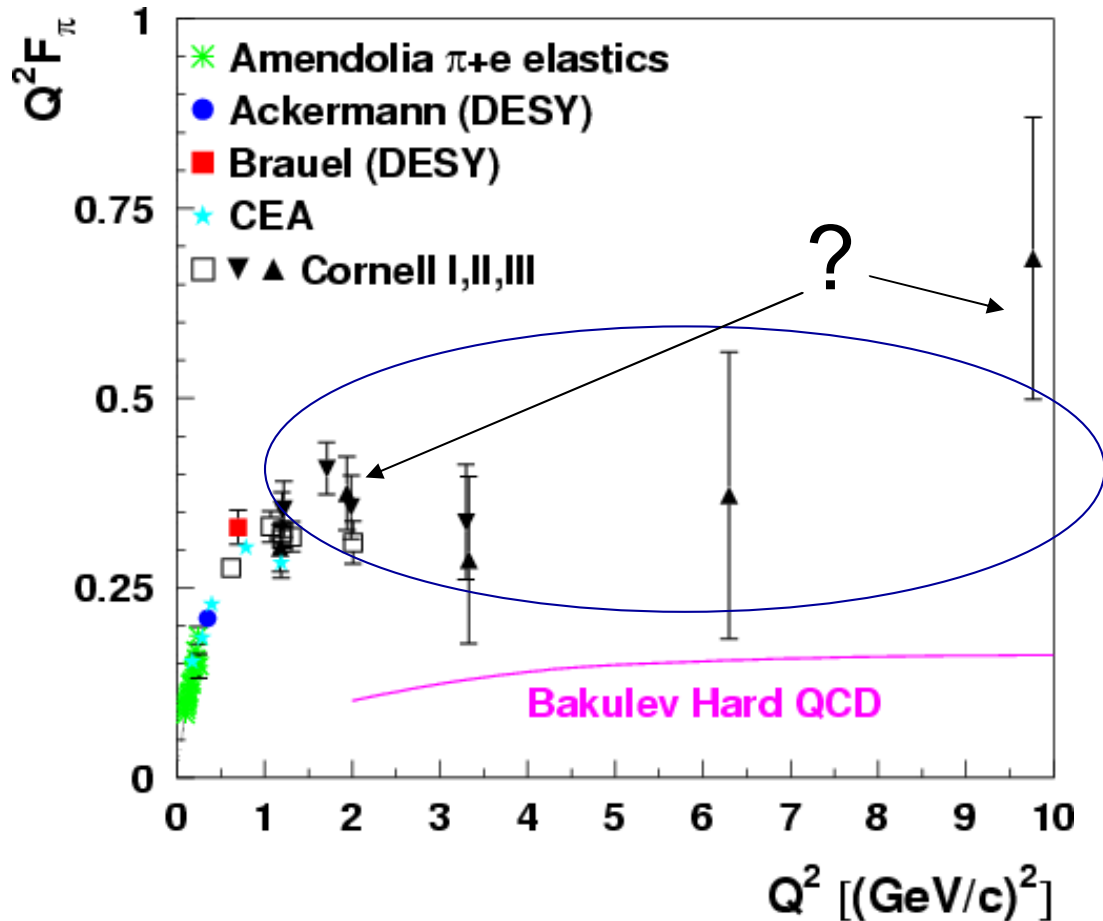
$ep \rightarrow e' \pi^+ n$ data are obtained some distance from the $t = m_\pi^2$ (real π scattering) pole

- No reliable phenomenological extrapolation possible



A more reliable approach is to use a model incorporating the π^+ production mechanism and the 'spectator' nucleon to extract $F_\pi(Q^2)$ from measured σ_L .

World π^+ Data Set, 1997



Problematic L/T separation.

- Older data at larger Q^2 ($> 1 \text{ GeV}^2$) extracted F_π from unseparated cross sections.
- Used extrapolation of σ_T fit at low Q^2 to isolate σ_L .

Analysis based on assumptions with systematic errors that are difficult to quantify.

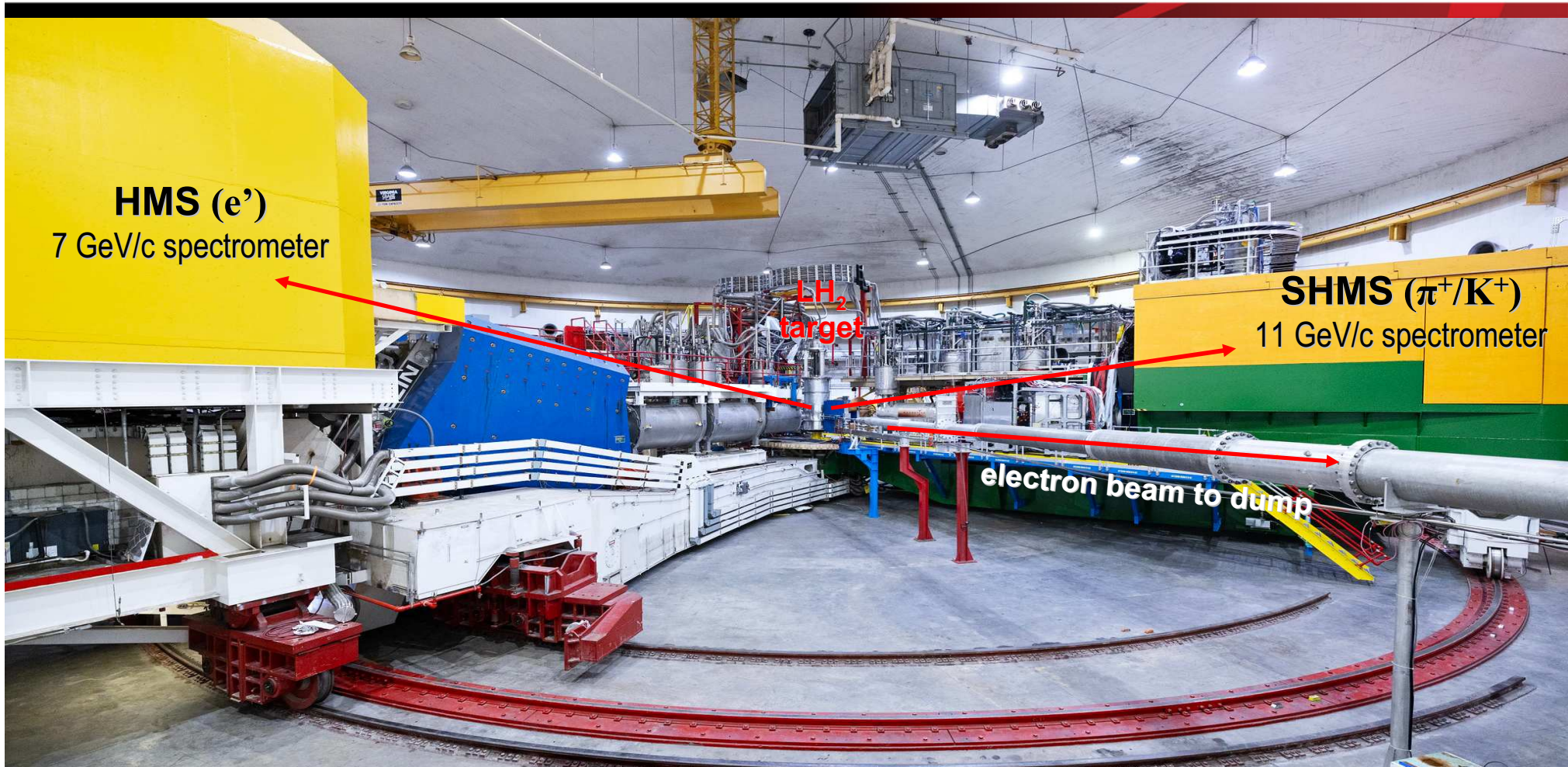
- Data taken far from pole, with $-t_{min}$ as high as $40 m_\pi^2$.

“[we] question whether F_π has been truly determined for large Q^2 .”

– C.E. Carlson, J. Milana, PRL **65** (1990) 1717

- The structures of the pion and kaon intimately connected to the deepest issues in our understanding of QCD
- **Despite the strong theoretical motivation, the structures of the pion and kaon are empirically much less well understood than that of the nucleon**
 - The comparative lack of data is due to the difficulty of the measurements, and the specialized requirements on the experimental facility
 - Jefferson Lab Hall C is unique worldwide in its capabilities and permits such measurements
- We have pursued a systematic program of pion measurements since the founding of JLab, and have performed our first measurements for the kaon
 - The end result of this program (to be completed early next decade) will be an order of magnitude increase in the world data set for exclusive pion and kaon reactions and form factors

Jefferson Lab Hall C



- **HMS and SHMS MAGNETIC OPTICS:**

- Point-to Point QQD for easy calibration of magnetic optics acceptance and event reconstruction
- SHMS Horizontal bend magnet allows spectrometer rotation to forward angles (5.5°); the HMS can rotate to a minimum of 10.5°

- **Rigid Support Structure and Connection to Pivot:** Provide Rapid & Remote Rotation, Pointing Accuracy & Reproducibility

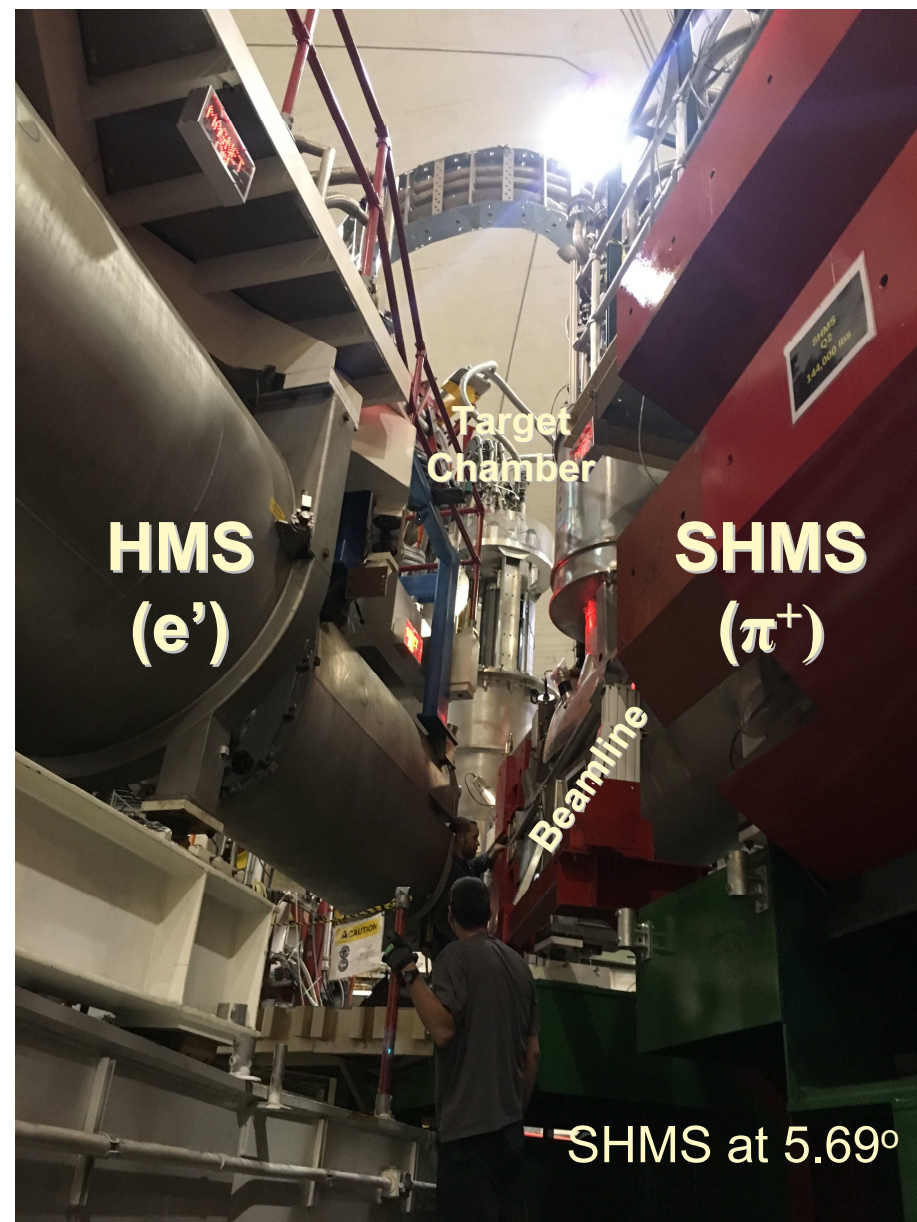
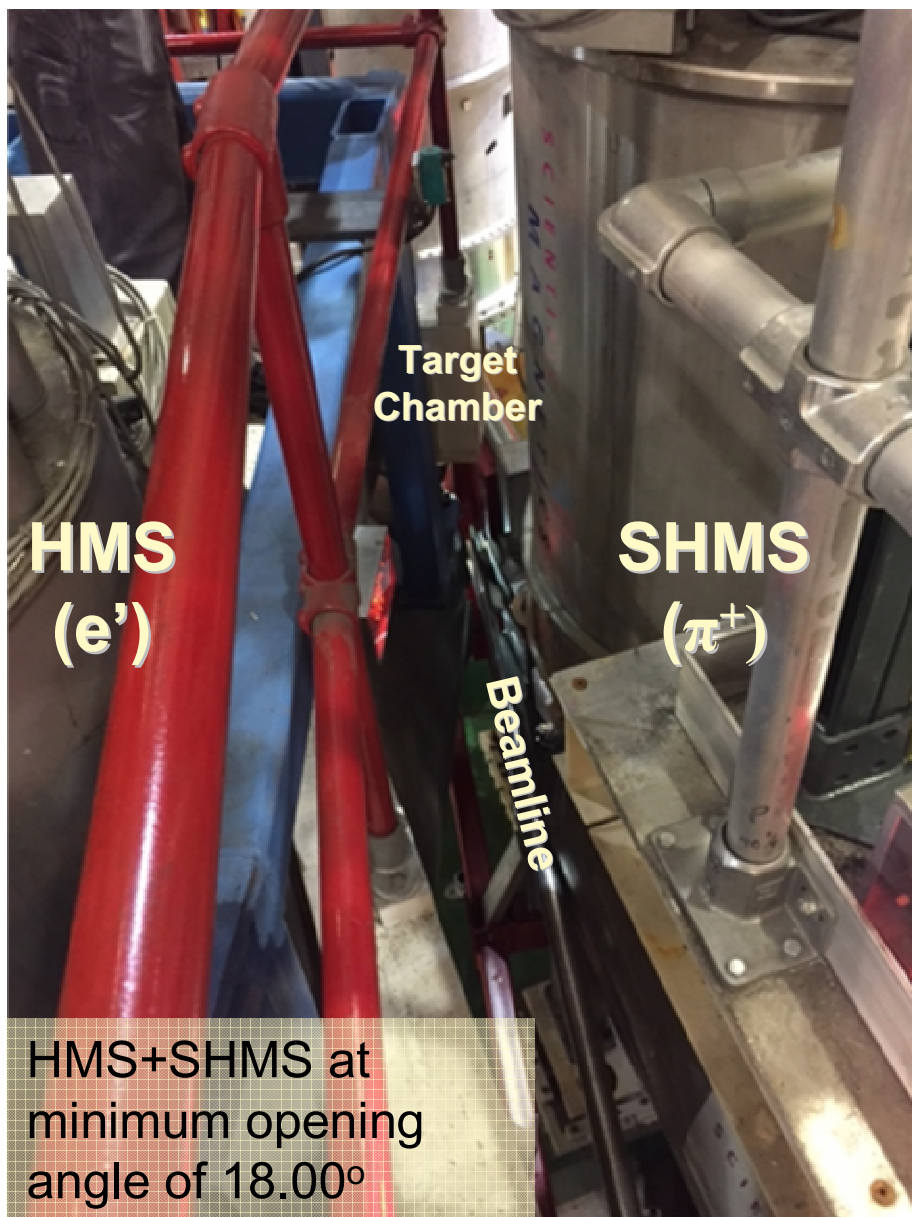
- **Spectrometer Detector Packages:** Drift Chambers, Hodoscopes, Cherenkovs, PbG Calorimeter

- **Well-Shielded Detector Enclosures permit measurements at Very High Luminosity:** $\sim 4 \times 10^{38} \text{ cm}^{-2} \text{ s}^{-1}$

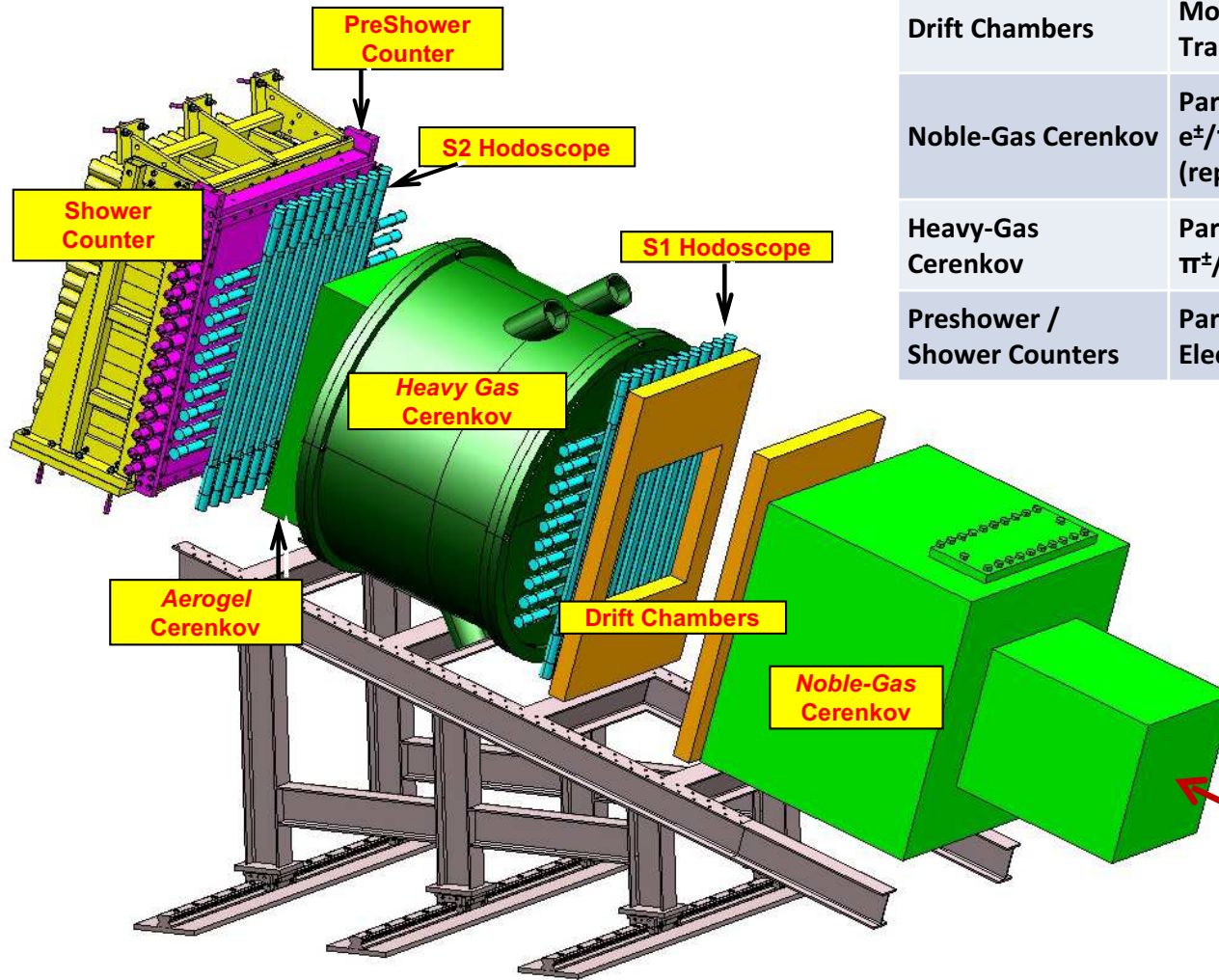
Hall C during Data Taking

π^+/K^+ FF experiments have challenging forward angle requirements

Garth Huber, huberg@uregina.ca



SHMS Focal Plane Detector System



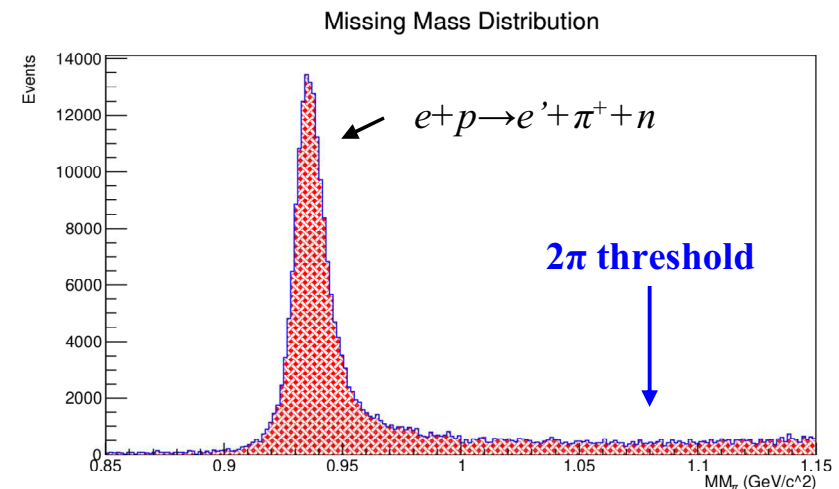
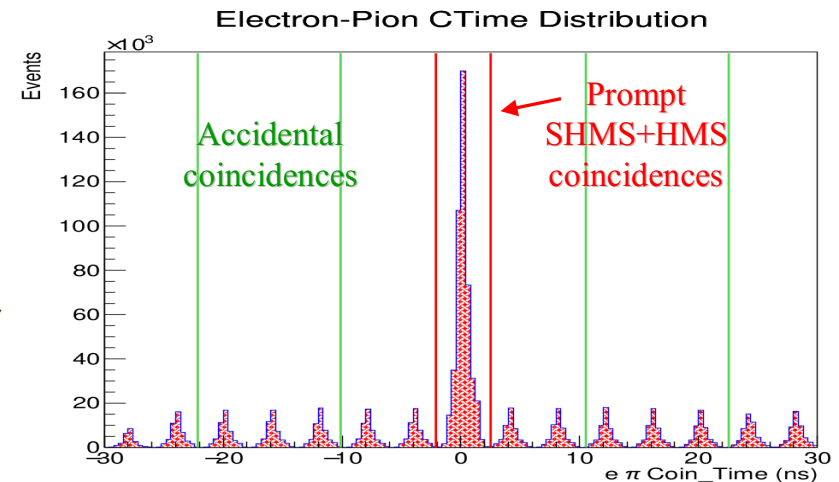
DETECTOR	PURPOSE	NOTES
S1XY, S2XY Hodoscopes	Lowest-level Trigger. Time reference	
Drift Chambers	Momentum Measurement. Tracking.	5mm max. drift 300 micron resolution
Noble-Gas Cerenkov	Particle ID, Trigger. $e^\pm/\pi^\pm$ at high momentum (replace by vacuum at low p)	Vary Ar/Ne mixture to set index at $\pi^\pm$ threshold.
Heavy-Gas Cerenkov	Particle ID, Trigger. $\pi^\pm/K^\pm$ discrimination	C_4F_8O – Vary pressure to set index at $K^\pm$ threshold
Preshower / Shower Counters	Particle ID, Trigger. Electron tag	

$ep \rightarrow e' \pi^+ n$ Event Selection

Coincidence measurement between charged pions in SHMS and electrons in HMS

Easy to isolate
exclusive channel

- Excellent particle identification
- CW beam minimizes “accidental” coincidences
- Missing mass resolution easily excludes 2-pion contributions



PionLT experiment E12-19-006 Data

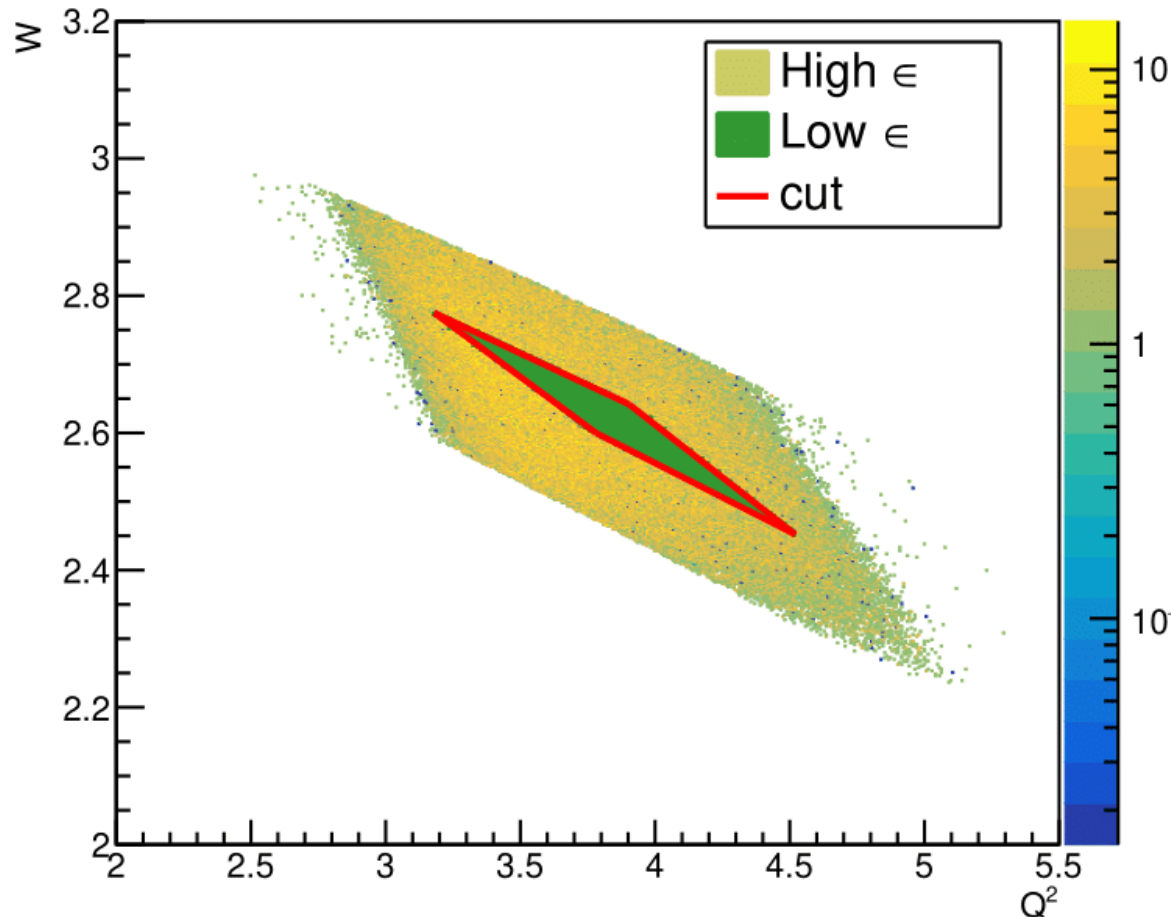
$Q^2=1.60$, $W=3.08$, $x=0.157$, $\varepsilon=0.685$

$E_{\text{beam}}=9.177$ GeV, $P_{\text{SHMS}}=+5.422$ GeV/c, $\theta_{\text{SHMS}}=10.26^\circ$ (left)

Plots by Muhammad Junaid (Regina PhD student)

Data at 2 Virtual Photon Polarizations (ϵ)

Garth Huber, huberg@uregina.ca



- Overlapping data at high and low ϵ are required for L/T separation
- Diamond cuts define (W, Q^2) acceptance at both ϵ

$ep \rightarrow e\pi^+n$ data

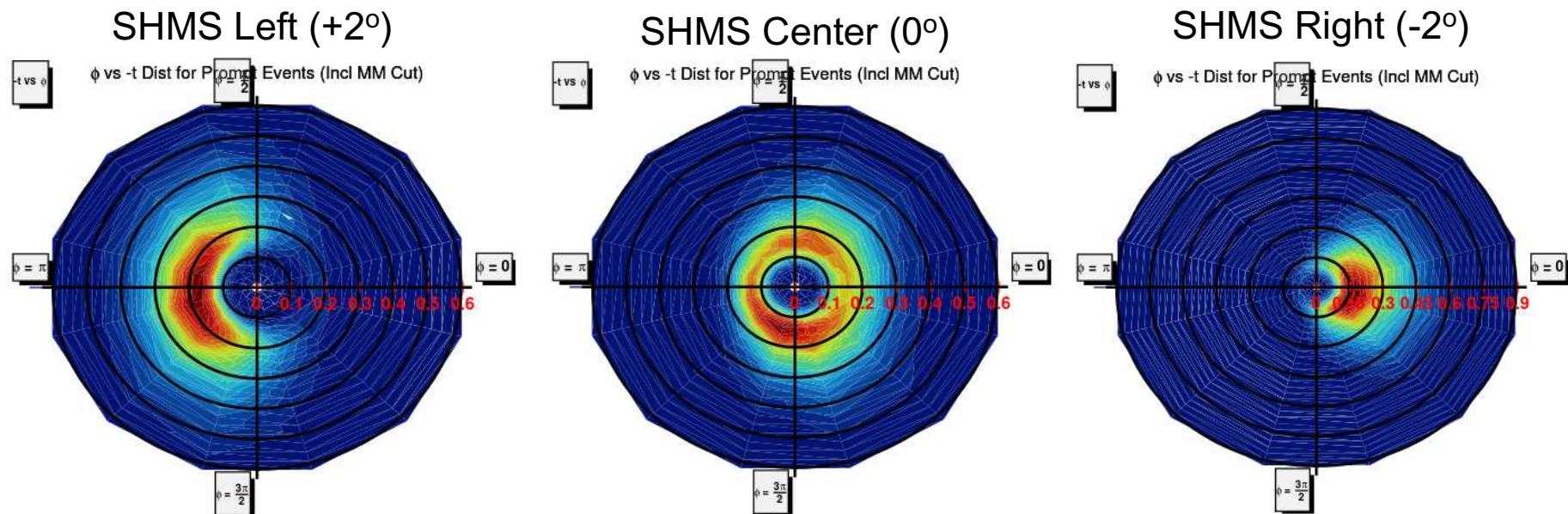
SHMS+HMS at $Q^2=3.85$, $W=2.62$

■ High $\epsilon=0.78$ ■ Low $\epsilon=0.29$

Plot by Muhammad Junaid (Regina PhD student)

The different pion arm (SHMS) settings are combined to give full azimuthal coverage

Radial coordinate ($-t$) Azimuthal coordinate (ϕ).



t - ϕ plots for: $Q^2=3.85$ $W=3.07$ High ϵ

• To control systematics, an excellent understanding of spectrometer acceptances is required

- Over-constrained $ep \rightarrow e'p'$ reaction, and inelastic $e+^{12}\text{C}$, used to calibrated spectrometer acceptances, momenta, kinematic offsets, efficiencies.
- Control of point-to-point systematic uncertainties crucial due to $1/\Delta\epsilon$ error amplification in σ_L

Plots by Nathan Heinrich (Regina PhD student)

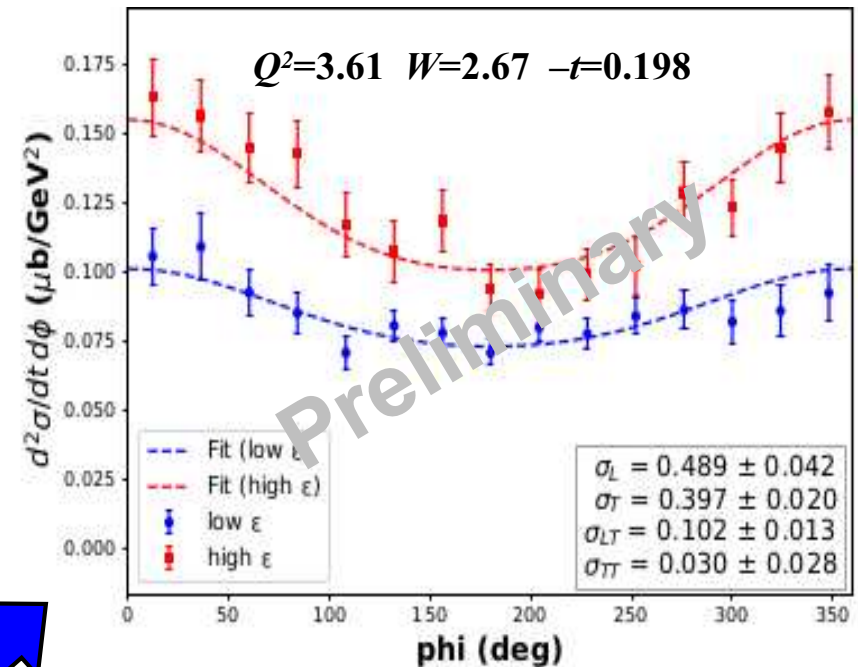
Measuring $d\sigma_L/dt$

$$2\pi \frac{d^2\sigma}{dt d\phi} = \epsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\epsilon(\epsilon+1)} \frac{d\sigma_{LT}}{dt} \cos \phi + \epsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$$

- Compare experimental yields to Monte Carlo of the experiment:
 - Radiative effects, pion decay, energy loss, multiple scattering
 - COSY model for spectrometer optics.

$$\left(\frac{d\sigma(\bar{W}, \bar{Q}^2, t, \phi)}{dt} \right)_{\text{exp}} = \frac{\langle Y_{\text{exp}} \rangle}{\langle Y_{\text{MC}} \rangle} \left(\frac{d\sigma(\bar{W}, \bar{Q}^2, t, \phi)}{dt} \right)_{\text{MC}}$$

- Extract σ_L by simultaneous fit using measured azimuthal angle (ϕ_π) and knowledge of photon polarization (ϵ)



Only Statistical Uncertainties Shown

Plot by Muhammad Junaid (Regina PhD student)

After σ_L is determined, a model is required to extract $F_\pi(Q^2)$

Model incorporates π^+ production mechanism and spectator neutron effects:

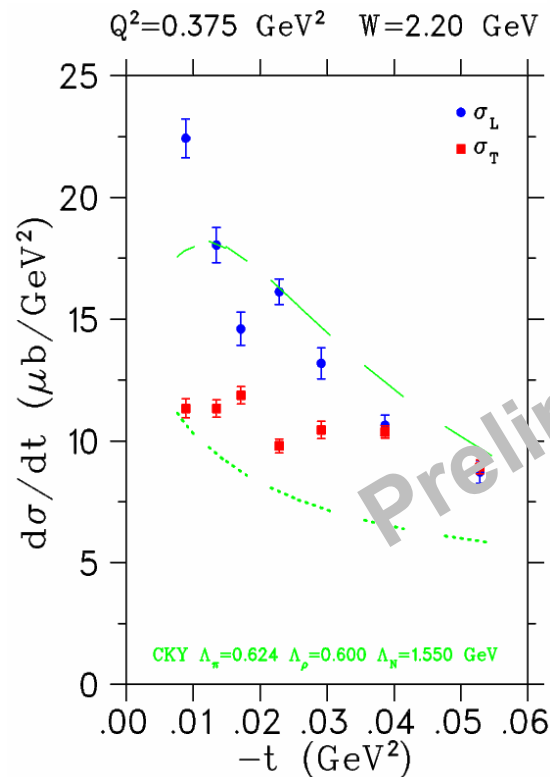
CKY Regge Model:

- Feynman propagator $\left(\frac{1}{t - m_\pi^2} \right)$ replaced by π and ρ Regge propagators.
 - Represents the exchange of a series of particles, compared to a single particle.
- Model parameters fixed from pion photoproduction.
- Free parameters: Λ_π , Λ_ρ , Λ_N (trajectory cutoff).

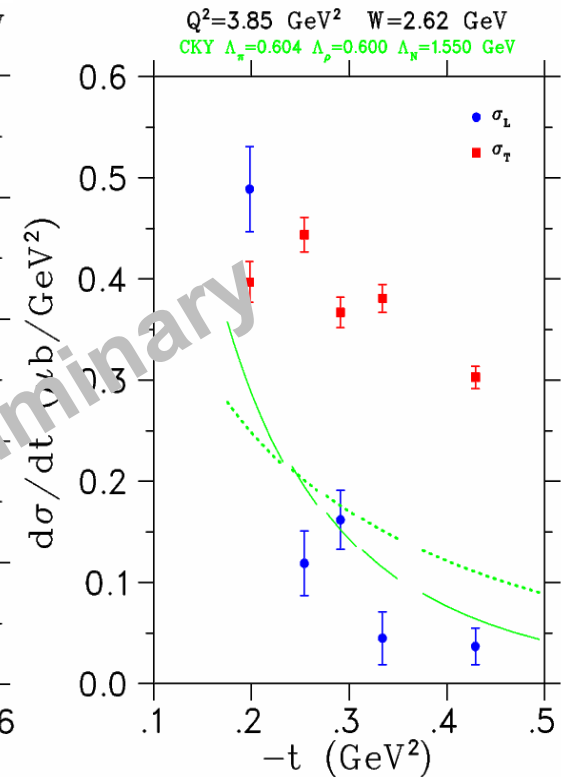
[Choi, Kong, Yu, JKorPhysSoc 67(2015)L1089, arXiv: 1508.00969]

$$F_\pi = \frac{1}{1 + Q^2 / \Lambda_\pi^2}$$

Fit of model to σ_L gives F_π at each Q^2 .



V.Kumar et al, publication in process



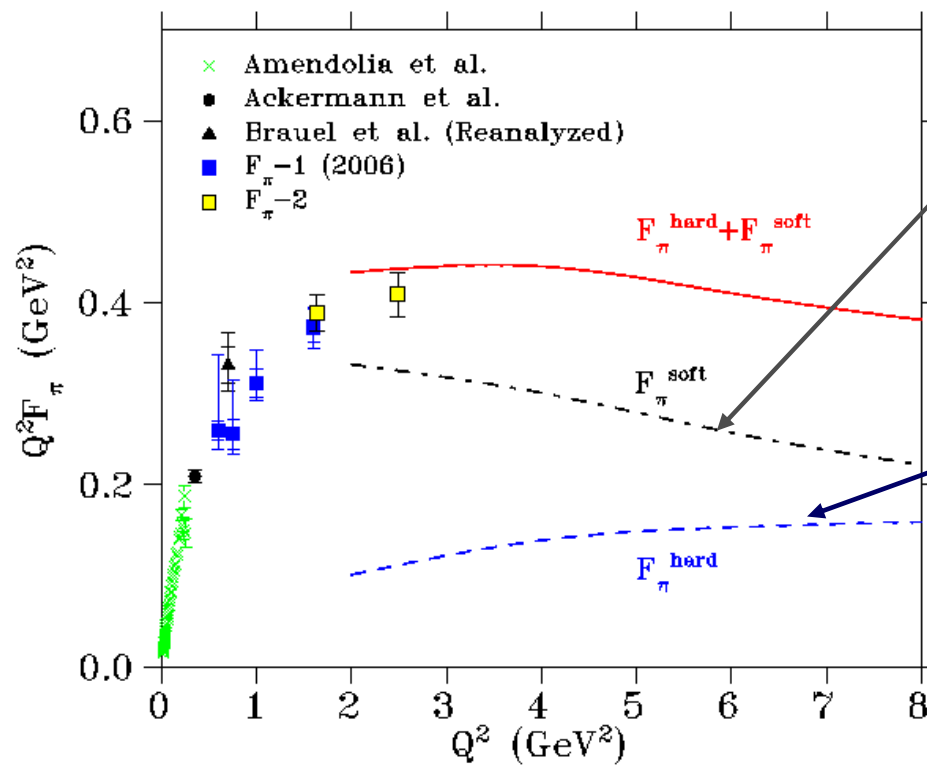
M. Junaid et al, publication in process

Error bars indicate statistical and random (pt-pt) systematic uncertainties in quadrature.

pQCD LO+NLO Calculation:

Analytic perturbation theory at the parton amplitude level.

A.P. Bakulev, K. Passek-Kumericki, W. Schroers, N.G. Stefanis, PRD 70 (2004) 033014.



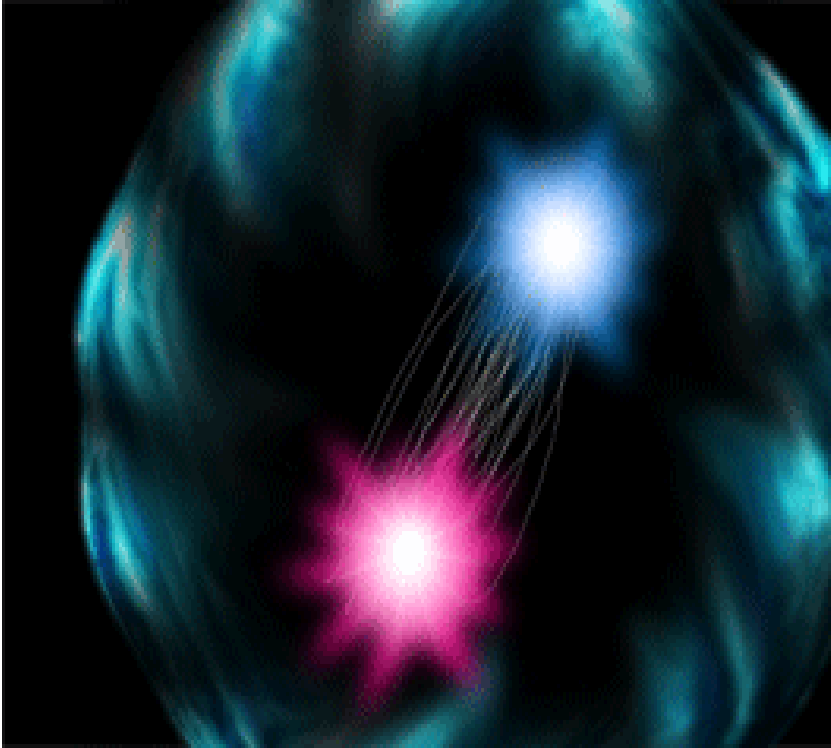
SOFT QCD:

- Extra piece needed to describe data.
- Model-dependent.
- Estimated from local quark-hadron duality model.

HARD QCD:

- Pion distribution amplitude consistent to 1σ level with CLEO $\pi\gamma$ transition data.
- Hard component is only slightly larger than that calculated with asymptotic DA in all considered schemes.

What do our 6 GeV results mean?



- Our F_π results are still far from the values predicted by pQCD.
- At the distance scales that our experiment has probed ($0.15 < r < 0.30$ fm), the π^+ structure is not governed by the two valence quarks.
- Virtual quarks and gluons dominate.
- **The pion is “softer” than the old Cornell results indicated.**

Our 12 GeV program extends these measurements to shorter distance scales to discover the scale where valence quarks dominate pion's structure.

→ Different theoretical viewpoints on whether higher-twist mechanisms dominate until very large momentum transfer or not.

Projected 12 GeV F_π Data

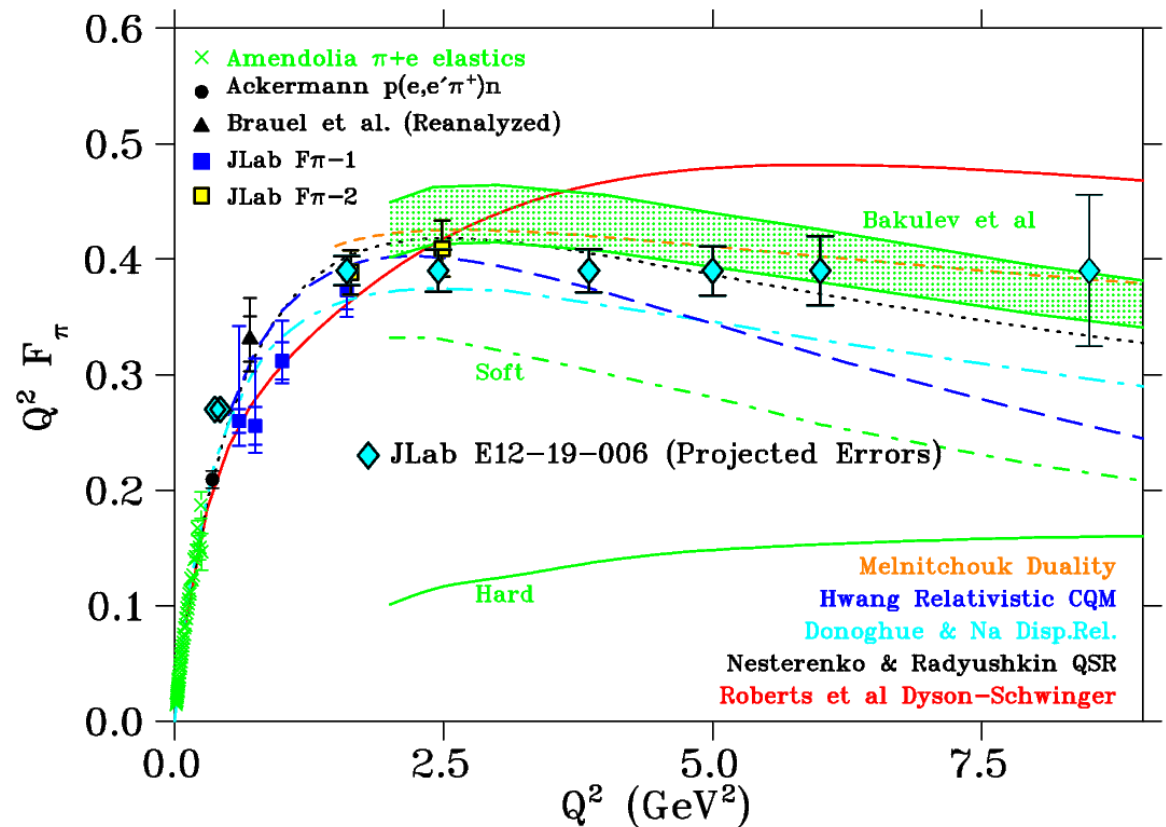
SHMS+HMS will allow measurement of F_π to much higher Q^2

No other facility worldwide can perform this measurement

*Data taking completed September 2022
(E12-19-006: GMH, D. Gaskell and T. Horn, spokespersons)*

y-positions of projected points are arbitrary

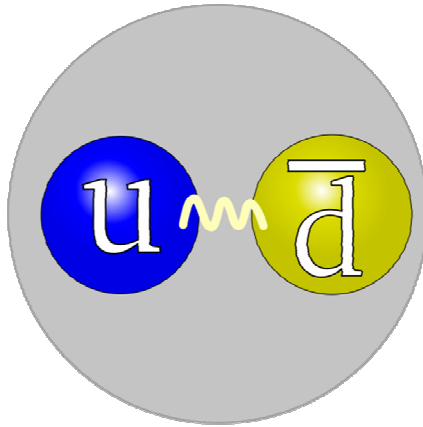
Error bars are calculated from obtained statistics and projected systematic uncertainties



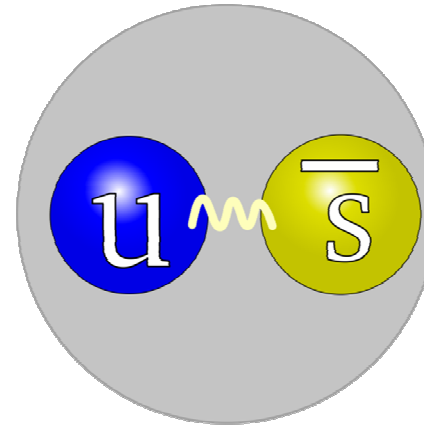
The $\sim 10\%$ measurement of F_π at $Q^2=8.5 \text{ GeV}^2$ is at higher $-t_{min}=0.45 \text{ GeV}^2$

The pion form factor is the clearest test case for studies of QCD's transition from non-perturbative to perturbative regions

The Charged Kaon – a 2nd QCD test case



π^+



K^+

- In the hard scattering limit, pQCD predicts that the π^+ and K^+ form factors will behave similarly

$$\frac{F_K(Q^2)}{F_\pi(Q^2)} \xrightarrow{Q^2 \rightarrow \infty} \frac{f_K^2}{f_\pi^2}$$

- It is important to compare the magnitudes and Q^2 -dependences of both form factors.

$ep \rightarrow e' K^+ \Lambda(\Sigma^0)$ Experiment

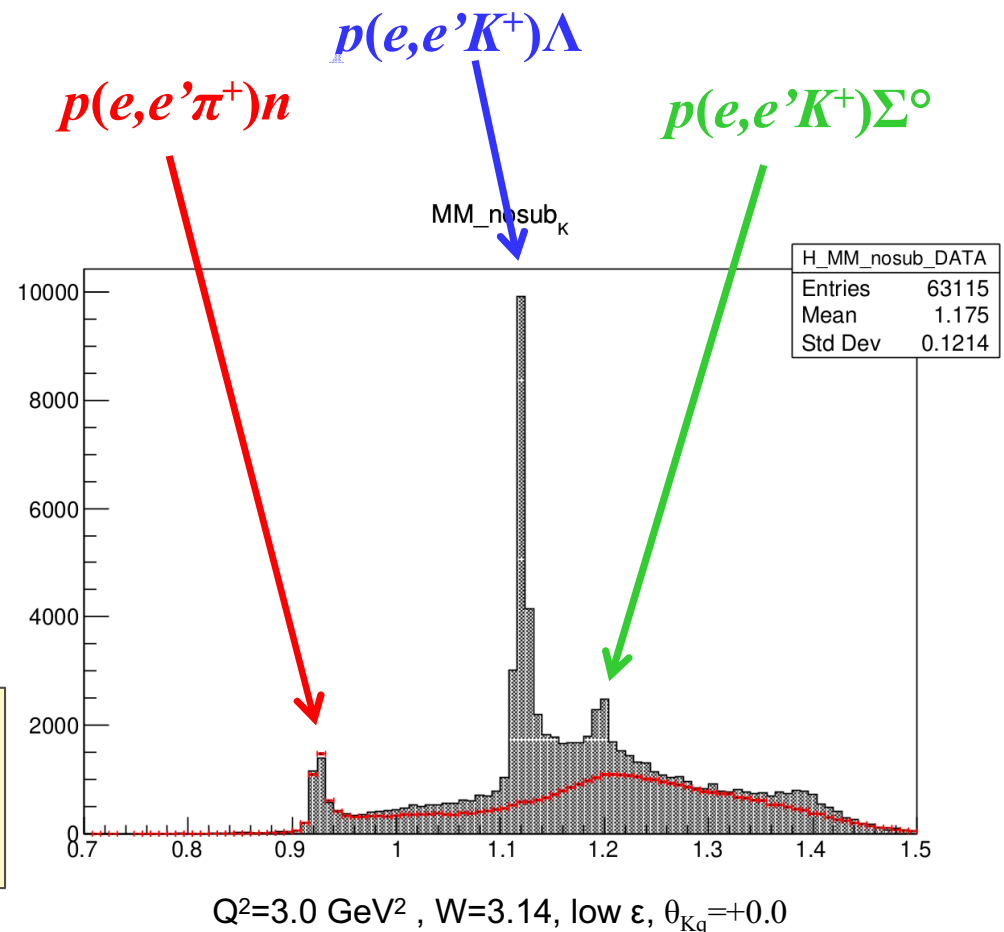
Isolate Exclusive Final States via Missing Mass

$$M_X = \sqrt{(E_{\text{det}} - E_{\text{init}})^2 - (p_{\text{det}} - p_{\text{init}})^2}$$

- Spectrometer coincidence acceptance allows for simultaneous studies of Λ and Σ^0 channels.

KaonLT experiment is probing issues relating to the extraction of the K^+ form from electroproduction data

$$\sigma_L \approx \frac{-2tQ^2}{(t - m_K^2)^2} k(eg_{K\Lambda N})^2 F_K^2(Q^2)$$



Plot by Richard Trotta (CUA/Virginia)

Kaon Form Factor Experiment Goals

- Measure the $-t$ dependence of the $ep \rightarrow e' K^+ \Lambda(\Sigma^0)$ cross section versus Q^2 and $W > 2.5$ GeV to search for evidence of K^+ pole dominance in σ_L
 - Separate the cross section components: L, T, LT, TT
 - First L/T measurement above the resonance region in K^+ production
- If warranted by the data, extract the Q^2 dependence of the kaon form factor to shed new light on QCD's transition to quark-gluon degrees of freedom.
- Even if we cannot extract the kaon form factor, the measurements are important.
 - $K^+ \Lambda$ and $K^+ \Sigma^0$ reaction mechanisms provide valuable information in our study of hadron structure
 - Flavor degrees of freedom provide important information for QCD model building and understanding of basic coupling constants

The past 25 years have seen good progress in developing a quantitative understanding of the electromagnetic structure of the lightest mesons and the nucleon

- Much credit goes to the continuous electron beam provided by the Jefferson Lab superconducting linac, and advances in electron scattering techniques.

QCD has shown itself to be a richer field than originally expected as a result of the improved level of precision of the data

In the next few years, we look forward to:

- More results for the pion and kaon form factors.
- Deeper understanding of the proton's charge and magnetic structure.

Will we begin to see the transition to the perturbative QCD regime?

Meson Form Factors require a Model

- Meson elastic form factors determined via the electroproduction technique are in principle model-dependent, although this dependence is reduced if σ_L data are taken at sufficiently low $-t$
- Our JLab 6 GeV studies indicate the method is reliable for low $-t < 0.4 \text{ GeV}^2$ $p(e, e' \pi^+)n$ data [GMH et al., PRC 78 (2008) 045203]
 - A recent theory paper [PRC 97 (2018) 015203] suggests the Sullivan process can provide a reliable pion target up to $-t=0.6 \text{ GeV}^2$
- It is important determine over what t -range the Sullivan process is reliable, as well as to verify the reliability of the models used to infer the pion form factor from $d\sigma_L/dt$ data
- The PionLT experiment has adopted a data-driven approach to address these to the greatest extent possible:
 - Check consistency of model with data
 - Extract form factor at several values of $-t_{min}$ for fixed Q^2
 - Test that the pole diagram is really the dominant contribution to the reaction mechanism
 - Verify that electroproduction technique yields results consistent with p-e elastic scattering at same Q^2

F_π Extraction from JLab data

- A model is required to extract F_π from $d\sigma_L/dt$
 - Fit of model to σ_L gives F_π at each Q^2

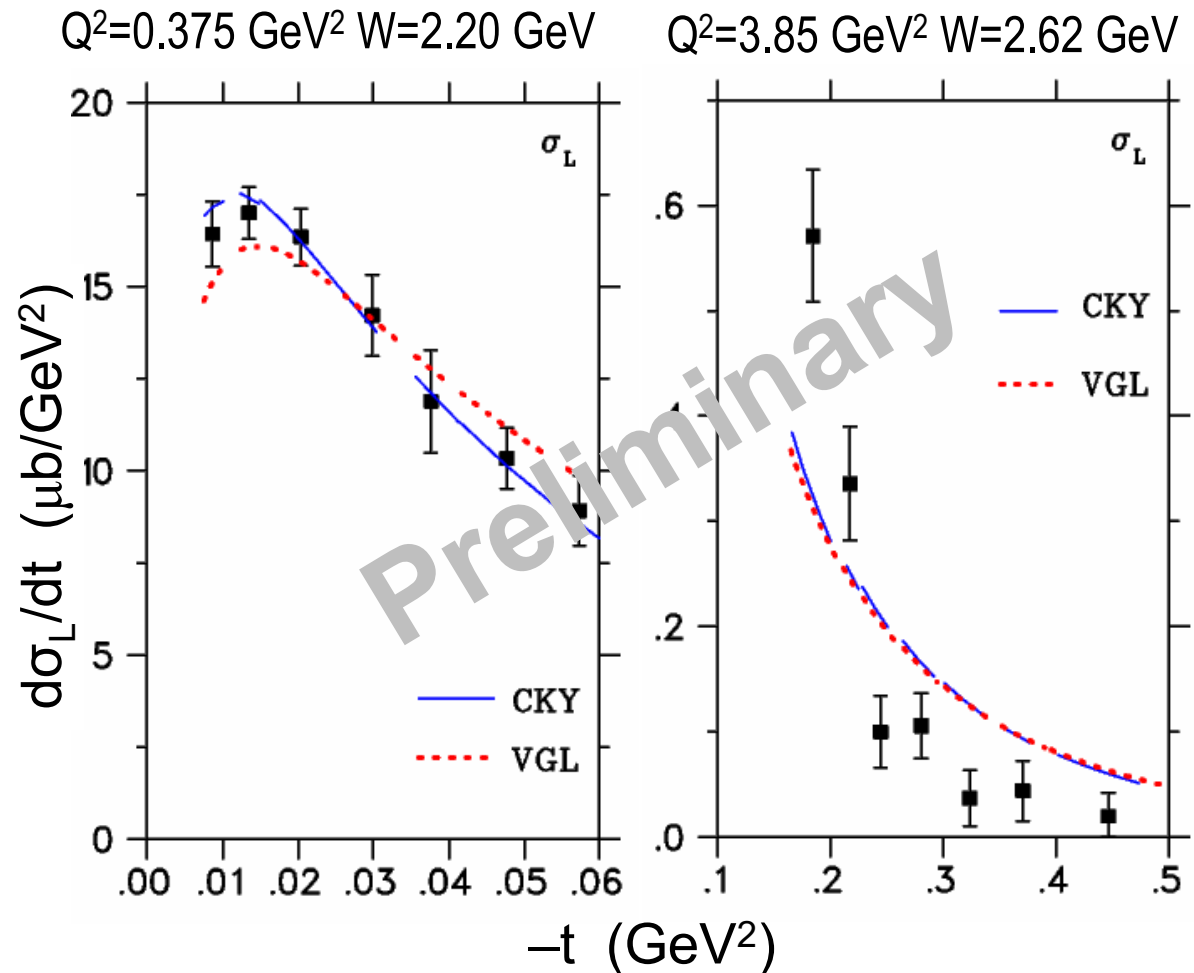
- JLab 6 GeV F_p expts used VGL Regge model

[Vanderhaeghen, Guidal, Laget, PRC 57(1998)1454]

- Most parameters fixed by photoproduction data
- At small $-t$, σ_L only sensitive to π Regge trajectory cutoff Λ_π

- Choi, Kong, Yu (CKY) Regge model allows 2nd way to extract F_π from σ_L data [JKorPhysSoc 67(2015)L1089, arXiv: 1508.00969]

- Perry, Kizilersu, Thomas model also now available [PLB 807(2020)135581]



V.Kumar et al, publication submitted

M. Junaid et al, publication in process

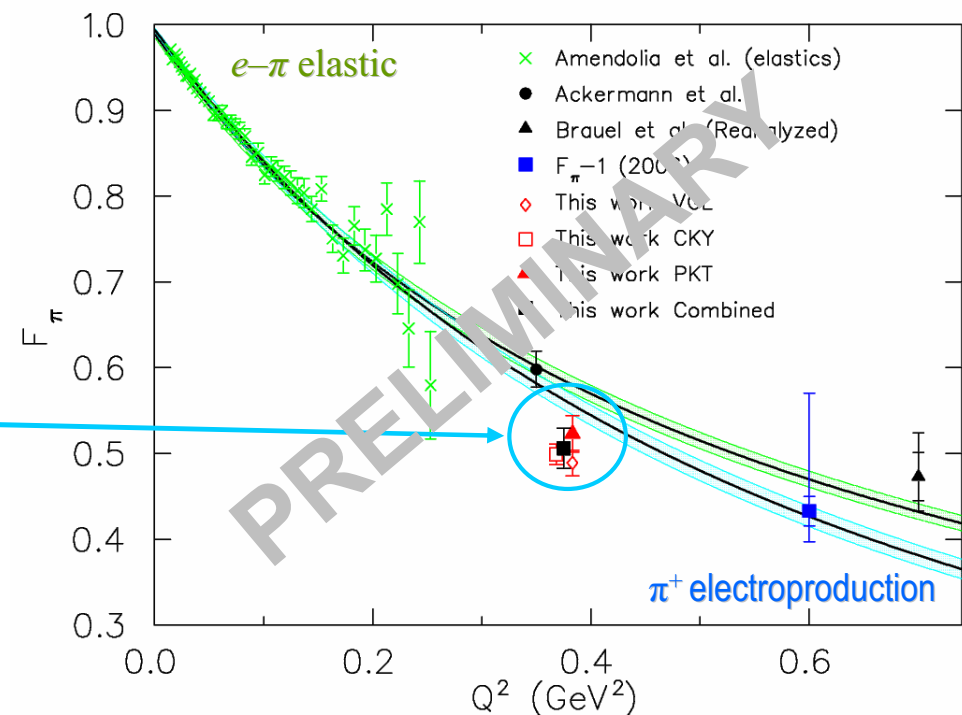
Low Q^2 Check of Electroproduction Technique

Directly compare $F_\pi(Q^2)$ values extracted from very low $-t$ electroproduction with values measured in elastic $e-\pi$ scattering

- $Q^2=0.35 \text{ GeV}^2$ data from DESY consistent with limit of elastic scattering data within uncertainties.

[H. Ackermann, et al., NP B137(1978)294]

- **PionLT acquired $p(e,e'\pi^+)n$ data for a low Q^2 test with much lower statistical and systematic uncertainties**



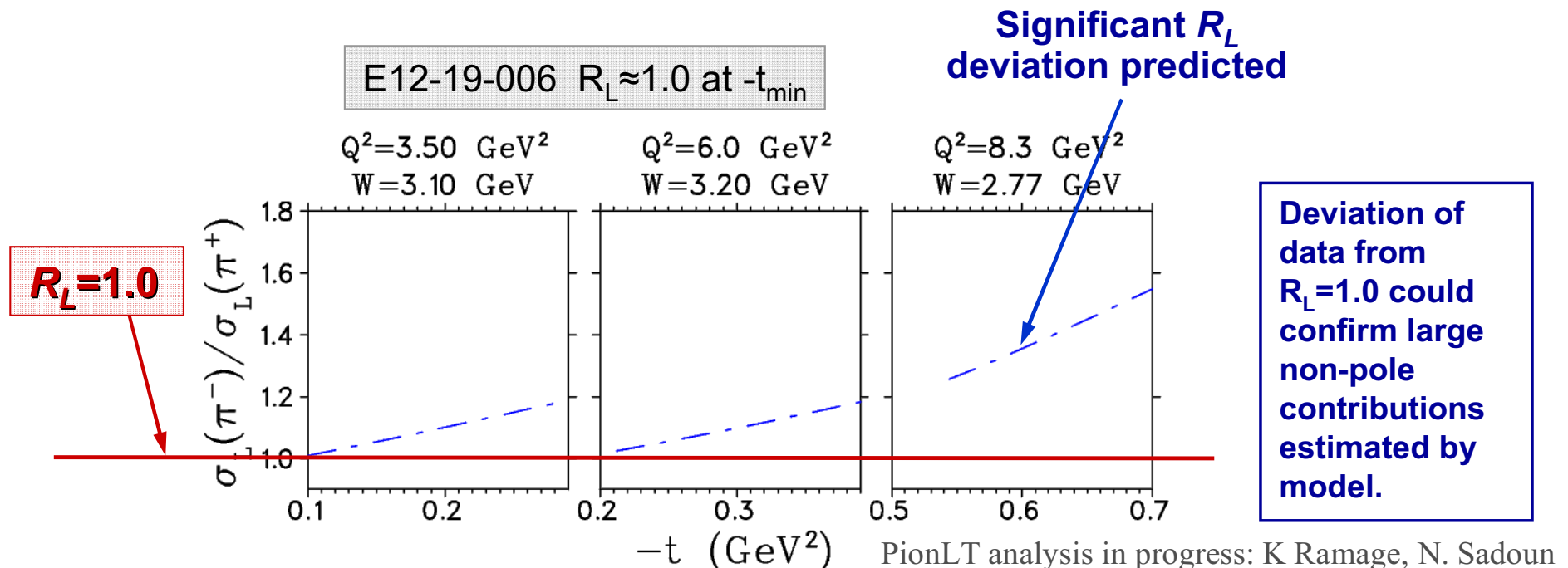
One way to understand non-pole to σ_L

Data-driven approach to better understand non-pole backgrounds at higher $-t$.

- Exclusive $^2\text{H}(e,e'\pi^+)nn$ and $^2\text{H}(e,e'\pi^-)pp$ L/T-separations.
- π^+ t -channel diagram is purely isovector (G-parity conservation).

$$R_L = \frac{\sigma_L[n(e,e'\pi^-)p]}{\sigma_L[p(e,e'\pi^+)n]} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2}$$

- Isoscalar backgrounds would distort ratio (e.g. $b_1(1235)$ in t -channel).



Another way to understand non-pole to σ_L

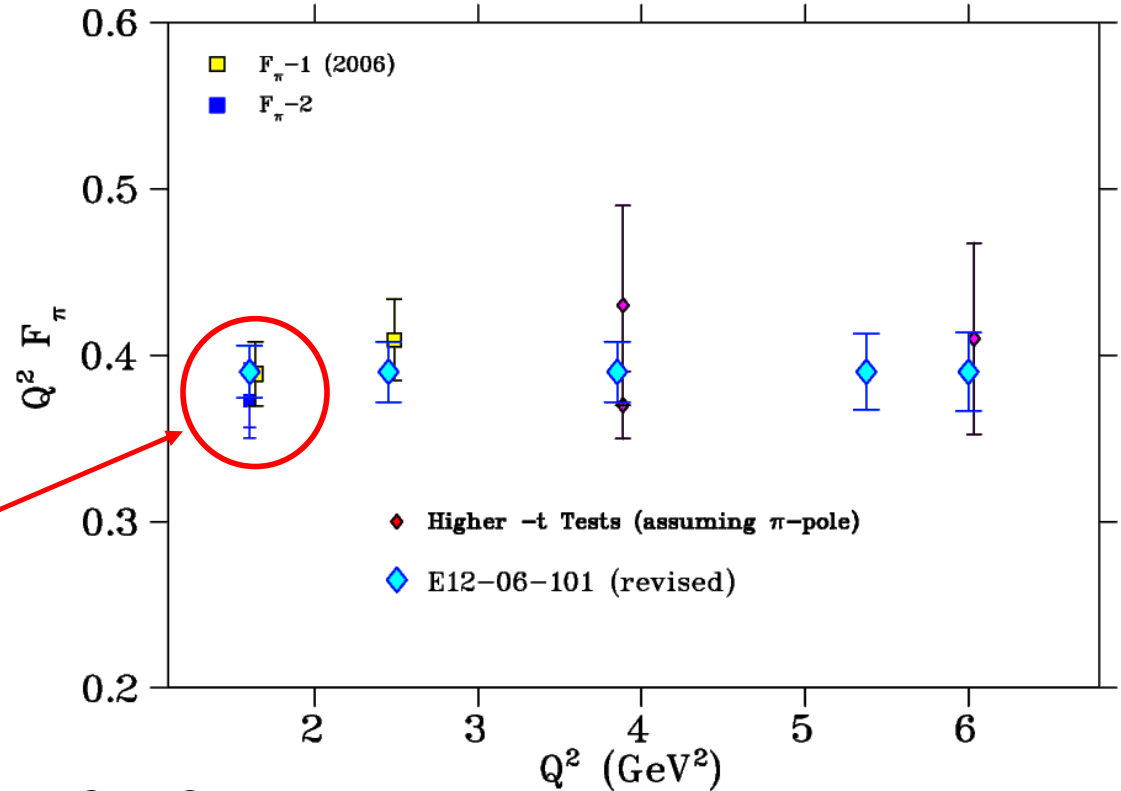
Test by extracting F_π at different distances from pole.

Expt: $F_{\pi-2}$, $-t_{min}=0.093 \text{ GeV}^2$
 $W=2.22 \text{ GeV}$.

$F_{\pi-1}$, $-t_{min}=0.15 \text{ GeV}^2$
 $W=1.95 \text{ GeV}$.

$W=2.22$ point 30% closer to pole.

→ Agreement $\sim 4\%$.



We have taken 12 GeV data for further tests:

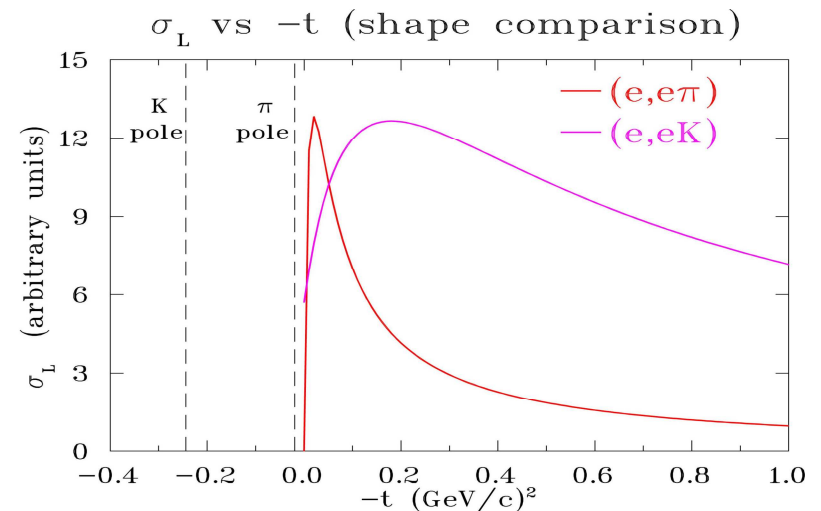
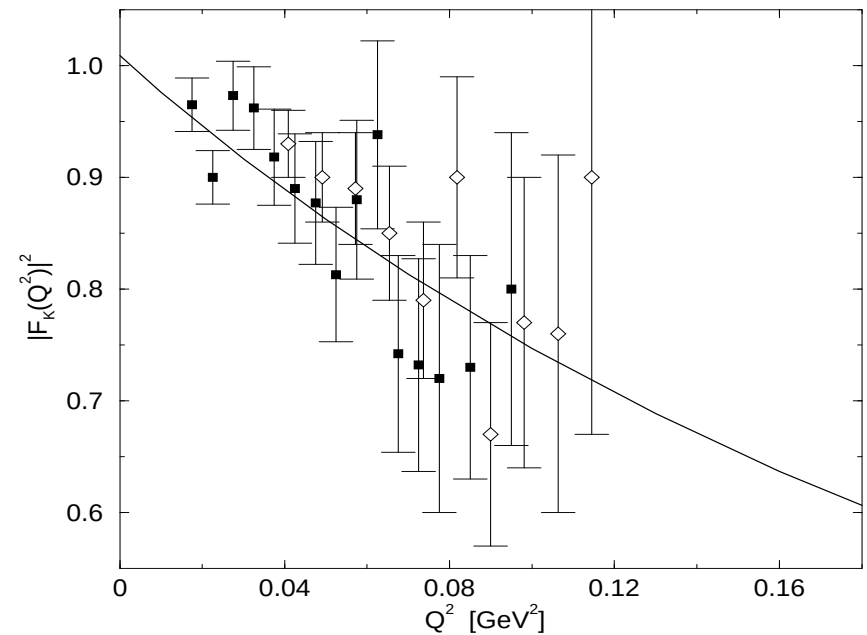
$Q^2=1.6 \text{ GeV}^2$	$-t_{min}=0.029 \text{ GeV}^2$	$W=3.00 \text{ GeV}$
$Q^2=2.45 \text{ GeV}^2$	$-t_{min}=0.048 \text{ GeV}^2$	$W=3.20 \text{ GeV}$
$Q^2=3.85 \text{ GeV}^2$	$-t_{min}=0.12, 0.21, 0.49 \text{ GeV}^2$	$W=3.07, 2.62, 2.02 \text{ GeV}$
$Q^2=6.0 \text{ GeV}^2$	$-t_{min}=0.21, 0.53 \text{ GeV}^2$	$W=3.19, 2.40 \text{ GeV}$

Measurement of K^+ Form Factor

- Similar to π^+ form factor, elastic K^+ scattering from electrons used to measure charged kaon form factor at low Q^2

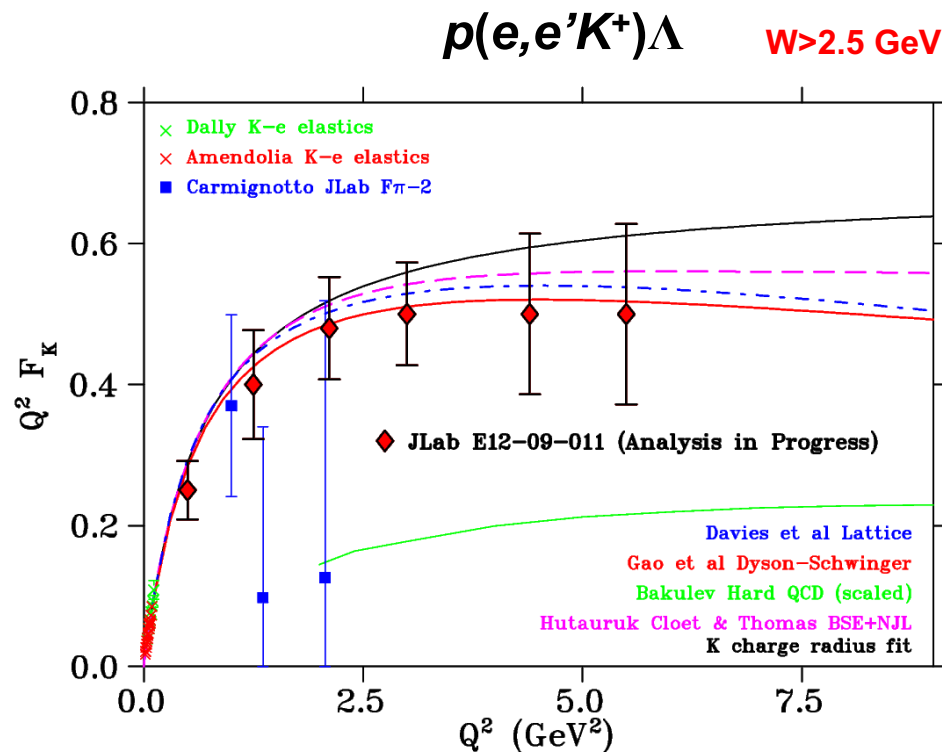
[Amendolia et al, PLB 178, 435 (1986)]

- World dataset on K^+ Form Factor only extends to $Q^2=0.12 \text{ GeV}^2$!
- Can “kaon cloud” of the proton be used in the same way as the pion to extract kaon form factor via $p(e,e'K^+)\Lambda$?
- Kaon pole further from kinematically allowed region
- Can we demonstrate that the “pole” term dominates the reaction mechanism?



Projected Uncertainties for K^+ Form Factor

- First measurement of F_K well above the resonance region.
- Measure form factor to $Q^2=3 \text{ GeV}^2$ with good overlap with elastic scattering data.
 - Limited by $-t < 0.2 \text{ GeV}^2$ requirement to minimize non-pole contributions.
- Data will provide an important second $q\bar{q}$ system for theoretical models, this time involving a strange quark.



Extraction of F_K from $Q^2 > 4 \text{ GeV}^2$ data is more uncertain, due to higher $-t_{\min}$

- *Partially completed as an early SHMS commissioning experiment: LT-separation*
(E12-09-011: T. Horn, G. Huber and P. Markowitz, spokespersons)
- *Data under analysis, expecting final results next year*
— C.K. Tam (CUA), R. Trotta (CUA/Virginia)

SHMS Particle Identification: +Hadrons

